

1 **IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review**

2  
3 **Chapter 1 - Assessment of Observed Changes and Responses**  
4 **in Natural and Managed Systems**

5  
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## 1 **Executive Summary**

2  
3 The IPCC WGII TAR found evidence that recent regional climate changes, particularly temperature  
4 increases, have already affected physical and biological systems. AR4 has analysed studies since  
5 the TAR showing changes in physical, biological and human systems mainly from 1970 to 2005 in  
6 relation to climate drivers and has found stronger quantitative evidence in a broader range of  
7 systems and sectors. The major climate factors are global and regional surface temperature  
8 increases, which have been strongly and widely documented in recent decades and which are like to  
9 influence many physical and biological processes.

10  
11 Evaluation of evidence on observed changes related to climate is made difficult because the  
12 observed responses of systems and sectors are influenced by many other factors. Non-climatic  
13 drivers can influence systems and sectors directly and/or indirectly through their effects on climate  
14 variables such as reflected solar radiation and evaporation. Socio-economic processes, including  
15 land-use change (e.g., agriculture to urban area), land-cover modification (e.g., forest to grasslands),  
16 technological change, and pollution are of major importance in affecting change in multiple systems  
17 and sectors. As adaptation is itself a potential response to changing climate, it, too, can be expected  
18 to dampen observed impacts. Despite these complexities, significant changes in systems and sectors  
19 related to changes in regional climate are detectable through a variety of analytical methods.

20  
21 **Many of the climate-driven observed changes in physical and biological systems can now be**  
22 **attributed to temperature increase caused by greenhouse gas emissions (high confidence).**

- 23  
24 • Observed responses in multiple systems and sectors since 1970 have been jointly attributed  
25 to anthropogenic climate change through attribution of the responses to regional warming  
26 and attribution of the regional warming to anthropogenic climate change.

27  
28 **For physical systems, there is more and stronger evidence since the TAR that climate change**  
29 **is affecting natural and managed systems in the cryosphere, while there is emerging evidence**  
30 **in hydrology and water resources, oceans, and coastal processes and zones that some systems**  
31 **and sectors are being affected (high confidence).**

32  
33 Changes in the cryosphere are manifested in the following ways:

- 34 • Accelerating changes in sea level rise, landscape appearance, slope stability in mountain  
35 permafrost, thawing of buried ice and destabilisation of moraines damming glacier lakes,  
36 and runoff from snow and glaciers in mountain regions.  
37 • Changes in Arctic mammals and Antarctic Peninsula fauna; and greening of the Arctic and  
38 the Antarctic Peninsula.  
39 • Effects on permafrost-based infrastructure and indigenous livelihoods in the Arctic, ski  
40 centres affected by decreasing snow cover in lower-elevation alpine areas, and changes in  
41 living conditions` and local tourism in many mountain regions around the world due to  
42 glacier retreat.

43  
44 These changes parallel the abundant evidence that the cryosphere, including Arctic sea ice,  
45 freshwater ice, ice shelves, Greenland ice sheet, alpine and Antarctic Peninsula glaciers and ice  
46 caps, snow cover, and permafrost, is undergoing melting in response to global warming.  
47 Recent evidence in hydrology and water resources shows that since the TAR, there is more  
48 evidence that the hydrological cycle is intensifying in regard to runoff /streamflow, droughts and  
49 floods, thermal structure of lakes, and water quality:

- 50 • There is an increasing trend in runoff in large basins in the Eurasian Arctic which agrees  
51 with recent regional rainfall trends and permafrost melting.

- 1       • Areas most affected by increasing long-term droughts, decreasing runoff, and decreases in  
2       some lake levels related in some cases to human activities, are located in drier regions.  
3       However, in wetter areas there is no consistent pattern of trends.  
4       • Lakes and rivers around the world are warming, with effects on thermal structure and lake  
5       chemistry.

6  
7   Ocean acidification is occurring although the impacts, for example on corals and the marine  
8   biosphere are as yet uncertain.

- 9       • Evidence indicates that the average pH of surface sea water has fallen by 0.1 units in the last  
10       200 years. This represents a 30% increase in the concentration of hydrogen ions in the  
11       surface oceans.

12  
13   Coastal processes and zones indicate evidence that:

- 14       • Sea-level rise, enhanced wave heights, and increased intensity of storms are affecting some  
15       coastal regions distant from human modification, e.g., polar areas and barrier beaches,  
16       mainly through coastal erosion.  
17       • Although local sea-level rise is contributing to losses of coastal wetlands and mangroves,  
18       and increased damages from coastal flooding in many areas, human modifications of coasts,  
19       such as increased construction in vulnerable zones, play an important role as well.  
20       • In many coastal regions, local sea level rise exceeds the global trend of ~1.7mm/yr, due to  
21       both climate change (thermal expansion of seawater and meltwater additions) and local land  
22       subsidence. These areas are more vulnerable to coastal flooding, shoreline erosion, and  
23       losses of wetlands.

24  
25   **There is more evidence from a wider range of species and communities in terrestrial**  
26   **ecosystems that recent warming is already strongly affecting natural biological systems. There**  
27   **is substantial new evidence in marine and freshwater systems relating changes to warming.**  
28   **The evidence shows that both terrestrial and marine biological systems are now being**  
29   **strongly influenced by observed warming (very high confidence).**

30  
31   In terrestrial biological systems:

- 32       • The overwhelming majority of studies exhibiting significant warming impacts on terrestrial  
33       species reveal consistent responses to regional climate trends, including poleward and  
34       elevational range expansions of flora and fauna.  
35       • Responses of terrestrial species to warming across the northern hemisphere are well  
36       documented by phenological changes, especially the earlier onset of spring events and  
37       lengthening of the growing season.  
38       • Changes in abundance for certain species over the last few decades have been attributed to  
39       climate change, including a few key butterfly examples of disappearance.

40  
41   In marine and freshwater biological systems:

- 42       • Many observed changes in phenology and distribution have been associated with rising  
43       water temperatures, as well as changes in salinity, oxygen levels, and circulation. The  
44       documented poleward movement of plankton and fish by 10 degrees latitude over a period  
45       of 4 decades in the North Atlantic is larger than any documented terrestrial study.  
46       • Climate change and variability, in combination with human impacts, have already caused  
47       substantial damage to coral reefs.  
48       • Warming lake and rivers are affecting abundance and productivity, community composition,  
49       phenology, distribution and migration.

50  
51   **Although responses to recent climate changes in human systems are difficult to detect due to**

1 **multiple non-climate driving forces and the presence of adaptation, effects are now detectable**  
2 **in a few agricultural and health systems (medium confidence).**

3  
4 Regarding agriculture and forestry:

- 5 • In temperate regions in large parts of North America and Europe, there is an advance in  
6 phenology, with limited evidence documenting management response to the shortening of  
7 crop-cycle duration. The lengthening of the growing season contributes to an observed  
8 increase in forest productivity.
- 9 • For arid regions such as the Sahel, reductions in precipitation and temperature increases on  
10 decadal scales have contributed to lower crop yields.
- 11 • The effects of gradual warming to-date are of limited consequence for crop production in  
12 comparison with other factors, except for viticulture, with documented improvement of  
13 grape quality in Europe and the U.S. However, both the agriculture and forestry sectors have  
14 shown vulnerability to recent extremes in heat, droughts, and floods.

15  
16 Regarding human health:

- 17 • While there is little evidence of climate change currently having widespread significant  
18 detectable effects on human health, there is emerging evidence that there have been changes  
19 in the distribution of some vectors of human diseases, such as ticks in Sweden; and of  
20 changes in the seasonal production of pollens that cause allergenic diseases in Europe.
- 21 • An increase in high temperature extremes, which is an important exposure for human health,  
22 has been associated with excess mortality during the 2003 heatwave in Europe, although  
23 health effects related to increasing heatwaves elsewhere have not been demonstrated.

24  
25 **Global losses reveal rapidly rising costs due to extreme weather-related events since the 1970s.**  
26 **While the dominant signal remains that of the significant increases in the values of exposure**  
27 **at risk, once losses are normalised for exposure, there still remains an underlying rising trend**  
28 **(medium confidence).**

- 29  
30 • For specific regions and perils, including extreme floods on some of the largest rivers, there  
31 is evidence for an increase in occurrence.
- 32 • For tropical cyclones, in particular in the Atlantic Ocean and Northwest Pacific, over the  
33 past 30 years, significant increases have occurred in the proportion of storms at the highest  
34 intensity (Categories 4 and 5) as well as in the cumulative ‘power dissipation’ of storms (a  
35 combination of intensity and duration) that correlates with increases in sea surface  
36 temperatures in the main cyclone development regions.

## 1.1 Introduction

The IPCC Working Group II Third Assessment Report found evidence that recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems, and preliminary evidence for effects in human systems (TAR Summary for Policymakers) (IPCC 2001). This chapter focuses on studies since the TAR that analyze significant changes in physical, biological, and human systems related to observed climate change. The studies are assessed in regard to current functional understanding of process-level responses to climate change and to factors that may confound such relationships, such as land-use change, urbanization, and pollution. Observations are also compared to simulated projections of impacts. The chapter considers the issue of ‘joint attribution,’ i.e., the determination of whether the observed changes may be related to anthropogenic climate forcing as well as natural forcings. Absence of evidence, i.e., cases where there is evidence of climate change without evidence of accompanying system or sector change, is also evaluated, since this is important for assessing whether responses to recent warming are systematic across regions, systems, and sectors.

### 1.1.1. Summary of observed changes in TAR

The WGI TAR described an increasing body of observations that gave a collective picture of a warming world and other changes in the climate system (IPCC 2001). WGII TAR documented methods of detecting observed changes, characterized the processes involved, and summarized the studies across multiple systems (Sections 2.2, 5.2.1, and 19.1) (IPCC 2001). Besides evidence in physical and biological systems related to warming, the IPCC WGII TAR also found preliminary indications that some human systems had been affected by recent increases in floods and droughts in some regions.

Changes in physical systems:

- *Sea ice:* Arctic sea-ice extent had declined by about 10-15% since the 1950s. No significant trends in Antarctic sea-ice extent were apparent.
- *Glaciers and Permafrost:* Mountain glaciers and ice caps were receding on all continents, and Northern Hemisphere permafrost was thawing.
- *Snow cover:* Extent of snow cover in the Northern Hemisphere had decreased ~10% since the late 1960s and 1970s.
- *Snowmelt and runoff:* Snow and runoff had occurred increasingly earlier in California since the late 1940s.
- *Lake and river ice:* Annual duration of lake- and river-ice cover in Northern Hemisphere mid and high latitudes had been reduced by about 2 weeks and become more variable.

Changes in biological systems:

- *Range:* Plant and animal ranges had shifted poleward and higher in elevation.
- *Abundance:* Within the ranges of some plants and animals, population sizes had changed, increasing in some areas and declining in others.
- *Phenology:* Timing of many lifecycle events, such as blooming, migration, and insect emergence, had shifted earlier in the spring and often later in the fall.
- *Differential change:* Species changed at different speeds and in different directions, causing a decoupling of species interactions (e.g., predator-prey relationships).

Preliminary evidence for changes in human systems:

- *Damages due to droughts and floods:* Damages had been related to persistent low rainfall in the Sahelian region of Africa and to increased precipitation extremes in North America.

1

2 *1.1.2 Scope and goals of chapter*

3

4 The aim of this chapter is to assess studies of observed changes in systems and sectors related to  
5 recent climate change, particularly temperature rise from 1970 to 2005, in order to advance  
6 understanding of the effects of climate change. Temperature rise is selected because it has a strong  
7 and widespread documented signal in recent decades and because it is an important influence on  
8 many physical and biological processes. The chapter evaluates the accumulating body of evidence  
9 with regard to the following questions:

- 10 1. Can changes in systems and sectors related to changing regional climate be detected?
- 11 2. Are observed changes consistent with functional understanding and modelled predictions of  
12 climate impacts?
- 13 3. Are observed changes prevalent across diverse systems, multiple sectors, and geographic  
14 regions and are there coherent patterns of change?
- 15 4. Do observed changes provide information about adaptation and vulnerability?
- 16 5. Can the observed changes be attributed to anthropogenic climate forcing?

17

18 The chapter reviews data sources and methods of detection of observed changes, investigating the  
19 roles of climate (including climate extremes and decadal climate variability) and non-climate  
20 drivers of change. A key focus is the analysis of evidence of no change, i.e., regions with  
21 documented warming trends, but with little or no documented changes or responses in systems or  
22 sectors. Evidence is then assessed regarding recent observed changes in sectors and systems  
23 relevant to Working Group II: cryosphere, hydrology and water resources, coastal processes and  
24 zones, marine and freshwater biological systems, terrestrial biological systems, agriculture and  
25 forestry, human health, and disasters and hazards. Evidence regarding other socio-economic effects,  
26 including energy use and tourism, is also assessed.

27

28 After assessing the state of knowledge on observed changes in the individual systems and sectors,  
29 we then assess studies that use techniques of larger-scale aggregation, including meta-analyses.  
30 Such studies relate observed changes in systems and sectors to regional climate trends, and analyze  
31 possible relationships to large-scale natural climate variations systems, such as ENSO and the  
32 NAO, and to anthropogenic climate change at the global scale. From the studies assessed in  
33 individual systems and sectors, a subset is selected that fits criteria in regard to length of study and  
34 statistically significant trends in change in system or sector related to recent changes in temperature  
35 or other climate variables in order to assess the potential for ‘joint attribution’ of observed changes  
36 in systems and sectors to anthropogenic climate forcing.

37

38 In the chapter, the term ‘response’ is used to connote processes by which both natural and human  
39 systems react to the stimuli of changing climate conditions; ‘sensitivity’ is the degree to which a  
40 system is affected by climate-related stimuli. Where there are relevant studies, we evaluate the role  
41 of adaptation of human systems and their vulnerability to observed changes. The term ‘adaptation’  
42 is used only for human systems; a related term in biological systems is ‘acclimation.’

43

44 Indigenous knowledge of observed changes is considered; sources of indigenous knowledge include  
45 the Arctic Climate Impact Assessment (ACIA 2004) and the Snowchange Project, a multi-year  
46 research and education project of the Circumpolar North (Helander and Mustonen 2004).

47

48 We recognize that there is a notable lack of geographic balance in literature on observed changes in  
49 systems and sectors, with marked paucity of studies in developing countries. Possible reasons for  
50 this imbalance are lack of access by IPCC authors to studies carried out in developing countries,  
51 lack of research and published studies, lack of knowledge of system sensitivity, differing system-

1 responses to climate variables (e.g., the predominance of systems that may be less sensitive to  
2 temperature), lag effects in responses, resilience in systems, and the presence of adaptation. There is  
3 an urgent need to improve the observation networks of observed changes and to enhance data sets  
4 for physical and biological systems and socio-economic sectors, particularly in developing  
5 countries.

## 6 7 8 **1.2 Methods of detection and attribution of observed changes** 9

10 Detecting significant changes in observed climate and attributing these changes to specific causes  
11 has been discussed in earlier assessments by the IPCC (IPCC 2001). The detection and attribution  
12 of climate change is essentially a signal-to-noise problem, for which methods have been developed  
13 to enhance possible forced climate change signals and to reduce the noise associated with the  
14 natural variability of the climate system. Following usage in the TAR (Mitchell *et al.* 2001),  
15 *detection* is the process of demonstrating that an observed change is significantly different (in a  
16 statistical sense) than can be explained by natural internal variability. However, the detection of a  
17 change does not necessarily imply that its causes are understood.

18  
19 As noted in the TAR (Mitchell *et al.* 2001), *attribution* of climate change to anthropogenic causes  
20 (i.e., the isolation of cause and effect) involves statistical analysis and the assessment of multiple  
21 lines of evidence to demonstrate, within a pre-specified margin of error, that the observed changes  
22 are

- 23 • unlikely to be due entirely to internal variability;
- 24 • consistent with the estimated responses to the given combination of anthropogenic and natural  
25 forcing; and
- 26 • not consistent with alternative, physically-plausible explanations of recent climate change that  
27 exclude important elements of the given combination of forcings.

28 Chapter 9 in AR4 Volume 1 (Hegerl *et al.* 2007) provides the most recent assessment of attribution  
29 of climate change to anthropogenic causes, concentrating on observed changes in climate variables  
30 that can be directly simulated by climate models.

31  
32 Detecting significant observed changes in natural and managed systems and attributing these as  
33 probable responses to changes in climate, such as regional warming, are even more complex.  
34 Attribution of observed changes and responses in systems to anthropogenic forcing is usually a two-  
35 stage process (IPCC 2003). First, the observed change in a system must be demonstrated to be  
36 associated with an observed regional climate change with a specified degree of confidence, and not  
37 to some other local driving factor. The confounding influences of multiple drivers make attribution  
38 of observed responses to regional climate change more difficult. Second, the observed regional  
39 climate change must be attributed to anthropogenic causes with a similar degree of confidence.

40  
41 Following the definition of climate change attribution above, the *attribution* of changes in these  
42 systems to regional climate change involves statistical analysis and the assessment of multiple lines  
43 of evidence to demonstrate that the observed changes are:

- 44 • unlikely to be due entirely to natural internal climate variability or natural variability of the  
45 system;
- 46 • consistent with the estimated biophysical response to a given regional climate change; and
- 47 • not consistent with alternative, plausible explanations of the observed change that exclude  
48 regional climate change.

49 Then *joint attribution* of the observed change in natural or managed systems to anthropogenic  
50 climate change involves both the attribution of the observed change to regional climate change and  
51 the attribution of the regional climate change to anthropogenic causes. This process usually

1 involves linking regional climate change simulations from climate models with the expected  
2 response in the system, either through biophysical or statistical models or statistical assessment.  
3 Confidence in joint attribution statements must be lower than the confidence in either of the  
4 individual attribution steps alone due to the combination of the two separate statistical assessments.  
5  
6

### 7 *1.2.1 Climate and non-climate drivers of change*

8

9 Both climate and non-climate drivers affect sectors and systems. While climate is an important  
10 factor in some systems, a large number of non-climatic drivers influence observed responses of  
11 sectors and systems to climate variations, making analysis of the role of climate in observed  
12 changes challenging. Non-climatic drivers can influence systems and sectors directly and/or  
13 indirectly through their effects on climate variables such as albedo and soil-moisture regimes.  
14 Socio-economic processes, including land-use change (e.g., forestry to agriculture; agriculture to  
15 urban area) and land-cover modification (e.g., ecosystem degradation or restoration) are of major  
16 importance in affecting change in multiple systems and sectors. Furthermore, many systems and  
17 sectors are affected by various aspects of pollution (e.g., in the atmosphere, soil, and water).  
18

#### 19 *1.2.1.1 Climate drivers of change*

20

21 Climate is a key factor determining the characteristics and distributions of natural and managed  
22 systems, including the cryosphere, hydrology and water resources, marine and freshwater biological  
23 systems, terrestrial biological systems, agriculture, and forestry. For example, temperature is  
24 known to strongly influence the distribution and abundance patterns of both plants and animals, due  
25 to the physiological constraints of each species (Parmesan and Yohe 2003; Thomas *et al.* 2004).  
26 The dramatic changes in the distribution of plants and animals during the ice ages illustrate the way  
27 that climate can determine the distribution of species. Similarly, the geographical distribution of  
28 plants and animals in the current climate can vary greatly over short distances where there are large  
29 spatial variations of temperatures, such as cooler regions at higher elevations. Equivalent effects  
30 can be observed in other systems and sectors, such as the cryosphere. Hence, changes in  
31 temperature due to climate change are expected to be one of the important drivers of change in  
32 natural and managed systems.  
33

34 Many aspects of climate are important in determining the characteristics and distributions of  
35 systems, including temperature and rainfall, and their variability on all time scales from days to the  
36 seasonal cycle to interannual variations. While changes in all of these aspects of climate may drive  
37 changes in systems, we focus on the climate parameters for which it is easiest to identify changes as  
38 a possible response to anthropogenic forcing (with the largest signal-to-noise). Mean temperature  
39 (including daily maximum and minimum temperature) and the seasonal cycle in temperature over  
40 relatively large spatial areas show the clearest signals of change in the observed climate (IPCC  
41 2001). Precipitation has much larger variability than temperature on most space and time scales,  
42 and it is therefore much more difficult to identify as a clear driver of changes in systems.  
43

44 The climate in many regions has large multi-decadal variations, such as the Pacific decadal  
45 oscillation (PDO and decadal variations of El Niño-Southern Oscillation (ENSO)), or the Atlantic  
46 multi-decadal oscillation (AMO and decadal variations of the North Atlantic Oscillation (NAO)).  
47 These are associated with temperature and rainfall variations that may lead to changes in natural  
48 and managed systems. Hence, studies of observed changes that only span several decades may be  
49 able to attribute these changes to regional climate variations, but may not be able to separate the  
50 response to multi-decadal climate variations from that due to longer-term climate change.  
51

1 There are a number of other possible climatic drivers of changes in natural and managed systems.  
 2 These include increases in carbon dioxide concentration in the atmosphere, which aids growth in a  
 3 large group of plants but also leads to increased acidity in the oceans, and changes in solar radiation  
 4 due to changes in clouds or aerosol amounts, which affect photosynthesis. Global dimming, related  
 5 to observed reductions in solar irradiance at the surface, has been assessed by Working Group I  
 6 (Jones *et al.* 2007) and has not continued after about 1990 (IPCC, 2007, Vol. 1).  
 7

#### 8 1.2.1.2 *Non-climate drivers of change*

9  
 10 Non-climate drivers, such as land use, land degradation, urbanization, and pollution, affect  
 11 systems and sectors directly and indirectly through their effects on climate (Table 1.1). These  
 12 drivers can operate independently or also in association with one another (Lepers *et al.* 2004).  
 13 Complex feedbacks and interactions occur on all scales from local to global.  
 14

15 **Table 1.1: Examples of direct and indirect effects of non-climate drivers.**

Non-climate driver	Examples	Direct effects on systems	Effects on climate
Geological processes	Volcanic activity, earthquakes, tsunamis (e.g. Adams <i>et al.</i> 2003)	Lava flow, mudflows (lahars), ash fall, shock waves, coastal erosion, enhanced surface and basal melting of glaciers, rockfall and ice avalanches	Cooling from stratospheric aerosols, change in albedo
Land-use change	Conversion of forest to agriculture (e.g. Lepers <i>et al.</i> 2004)	Declines in wildlife habitat, biodiversity loss, increased soil erosion, nitrification	Change in albedo, lower evapotranspiration, altered water and heat balances (e.g. Bennett and Adams 2004)
	Urbanization and transportation (e.g. Kalnay and Cai 2003)	Ecosystem fragmentation, deterioration of air quality, increased runoff and water pollution (e.g. Turalioglu <i>et al.</i> 2005)	Change in albedo, urban heat island, local precipitation reduction, downwind precipitation increase, lower evaporation (e.g. Weissflog <i>et al.</i> 2004)
	Afforestation (e.g. Rudel <i>et al.</i> 2005)	Restoration of vegetative cover (e.g. Gao <i>et al.</i> 2002)	Change in albedo, altered water and energy balances, carbon sequestration
Land-cover modification	Ecosystem degradation (desertification)	Reduction in ecosystem services, reduction in biomass (e.g. Nyssen <i>et al.</i> 2004)	Changes in microclimate (e.g., Su <i>et al.</i> 2004)
Invasive species	Eucalyptus (Australia), tamarisk (US), Alaska lupin (Iceland)	Reduction of biodiversity, salination (e.g. Lee <i>et al.</i> 2006)	Change in water balance (e.g. Ladenburger <i>et al.</i> 2006)
Pollution	Tropospheric ozone, toxic waste, oil spills, exhaust, pesticides and herbicides (e.g. Pagliosa and Barbosa 2006)	Reduction in breeding success, species mortality, reduction in biodiversity, health impairment (e.g. Lee <i>et al.</i> 2006)	Direct and indirect aerosol effects on temperature and albedo

16  
 17 Socio-economic processes that drive land-use change include population growth, economic  
 18 development, trade, and migration; these processes can be observed and measured at global,

1 regional, and local scales (Goklany 1996). Earth observations from satellite and published statistical  
2 data demonstrate that land-use change, including that associated with the current rapid economic  
3 development in Asia and South America, is proceeding at an unprecedented rate (Rindfuss *et al.*  
4 2004). Land-use changes influence albedo, energy budget and evaporation, which can be quantified  
5 in terms of radiative forcing. Some studies have linked land-use change with changes in the  
6 planetary energy and water balances, as well as to changes in air quality and pollution that affect  
7 the greenhouse process itself (Pielke *et al.* 2002; Kalnay and Cai 2003). Pielke *et al.* (Pielke 2002)  
8 report that the impact of land-use changes on climate is greatest in Southeast Asia and in parts of  
9 Central and South America. Land-use and land-cover change can also strongly magnify the effects  
10 of extreme climatic events, both on direct health outcomes (e.g., heat mortality, injuries/fatalities  
11 from storms, and ecologically mediated infectious diseases (Patz *et al.* 2005). Intensification of land  
12 use, as well as the extent of land-use change, is also affecting the functioning of ecosystems and  
13 hence on emissions of greenhouse gases from soils, such as carbon dioxide and methane (NASA  
14 2004).

15  
16 There are also a large number of socioeconomic factors that can influence, obscure or enhance  
17 observed impacts of climatic change and must be taken into account when seeking the climatic  
18 signal or explaining observations of impacts and even adaptations. For example, the effects of sea  
19 level rise and extreme events are much greater when they occur in regions with growing  
20 populations, inadequate infrastructure, or high property prices (Pielke *et al.* 2003). The observed  
21 impacts of climate change on agriculture are largely determined by the ability of producers to  
22 access or afford irrigation, alternate varieties, markets, insurance, chemicals and agricultural  
23 extension, or to abandon agriculture for alternate livelihoods (Eakin 2000). The health impacts of  
24 climate change are influenced by demography (the elderly and very young), poverty (access to air  
25 conditioning), preventive technologies (pest control, immunization) and healthcare institutions.

### 26 27 28 **1.2.2 Data**

29  
30 Records typically decades in length are preferable for obtaining reliable findings of observed  
31 changes related to climate trends.

32  
33 *Ground-based observations.* Depending on the sector and system assessed (see 1.3), variable  
34 quantities of data in time and space are available in different locations around the globe, some of  
35 which have been collected for other purposes. The availability of suitable long-term geophysical  
36 and biological data is unbalanced, leading to reported examples predominantly from the Northern  
37 Hemisphere. Many data sources have not been fully tapped, such as fishery by-catch records,  
38 observations from botanical gardens and agricultural research stations, photographic archives  
39 (including aerial photography), and indigenous knowledge. Often these sources are not widely  
40 accessible as the records are not archived, or exist only on paper or in restricted formats, rather than  
41 in digital and easily-accessed form. However, in the last five to seven years, the number of studies  
42 investigating evidence of climate-related changes has markedly increased.

43  
44 Systematically collected network data (e.g., plant data from >120 000 locations monitored  
45 throughout Europe (Menzel *et al.* 2006) allow simultaneous analysis of responses and non-  
46 responses of many species or indicators over large areas. Investigating a suite of processes or  
47 species at numerous locations, such as all species of a given taxa in one area (e.g. Parmesan and  
48 Yohe 2003), also allows analysis of indicators or species with and without change. Examining one-  
49 to-several species or indicators at one or various locations provides understanding of how those  
50 species that are changing are shifting relative to warming (e.g. Root *et al.* 2003). Data from  
51 individual sites tend to have longer time series, whether continuously or intermittently monitored.

1 Together, these methods provide information on how a wide array of species from many regions are  
2 responding to climate warming.

3  
4 *Remote sensing.* Remote sensing, mainly by satellite (but also by conventional air photography) is a  
5 significant tool for observing changes in various systems and sectors at regional and global scales.  
6 Beginning with Landsat in 1973, time series of remote sensing data are now long enough to detect  
7 significant changes in terrestrial vegetation and marine productivity. Remote sensing is also used to  
8 characterize changes in glacier, snow, sea ice and freshwater ice extent from passive microwave  
9 data, radar observations from Radarsat or ERS and more recently from airborne and satellite-based  
10 laser altimetry (IceSat). High-resolution satellite imagery combined with geoinformatics are  
11 increasingly used now for observing, anticipating and assessing rapidly changing hazards related to  
12 snow, glaciers and permafrost in cold mountain regions (Huggel *et al.* 2004; Huggel *et al.* 2005;  
13 Kaab *et al.* 2005). Land-use changes are also observable from low-resolution sensors such as  
14 VEGETATION on SPOT 4 and 5, MODIS on Aqua and Terra, and MERIS on ENVISAT.  
15 However, time-series from these systems are only several years at present. Over time, they will  
16 allow quantification of geographical shifts in vegetation and temporal changes in phenology,  
17 productivity, forest fires, etc.

18  
19 A common application is the estimation of net primary productivity (through vegetation indices  
20 derived from reflectances in different wavelengths) (Fig. 1.1a) and the derivation of the mean  
21 absorbed fraction of Photosynthetic Active Radiation (PAR) (Nemani *et al.* 2003). These often rely  
22 on data from the NOAA-AVHRR satellites in operation from about 1980. A limitation in remotely  
23 sensed data lies in the lack of continuity and consistency in spatial and spectral resolution from  
24 successive sensors. This makes quantitative direct inter-comparison and calibration among sensors  
25 difficult and requires careful implementation of data processing and spectral normalization  
26 techniques (Trishchenko *et al.* 2002; Trishchenko *et al.* 2002; Cihlar *et al.* 2004). Significant  
27 progress in this direction has enabled an assessment of changes in Northern Hemisphere forest  
28 productivity (Zhou, Tucker *et al.* 2001) (see 1.3.6), although additional analyses are still required to  
29 determine the manitude of changes more precisely (Lanfredi *et al.* 2003; Simoniello *et al.* 2004;  
30 Stockli and Vidale 2004).

31  
32 To measure changes in the marine biological systems, the historical Coastal Zone Colour Scanner  
33 (CZCS) record (1972-1986) was reconstructed (Gregg and Conkright 2002) to achieve compatibility  
34 with the modern Sea-viewing Wide Field-of-view Sensor (SeaWiFS; 1997-present. Application of  
35 blending methodologies (Gregg and Conkright 2001; Gregg and Conkright 2002) where in situ data  
36 observations are merged with the satellite data, provide improvement of the residual errors of both  
37 the CZCS and SeaWiFS. The re-analyzed, blended satellite-in situ chlorophyll data records provide  
38 maximum compatibility and permit, for the first time, a quantitative analysis of the changes in global  
39 ocean primary production from the early-to-mid 1980s to the present (Fig. 1.1b)(Gregg *et al.* 2003).

40  
41

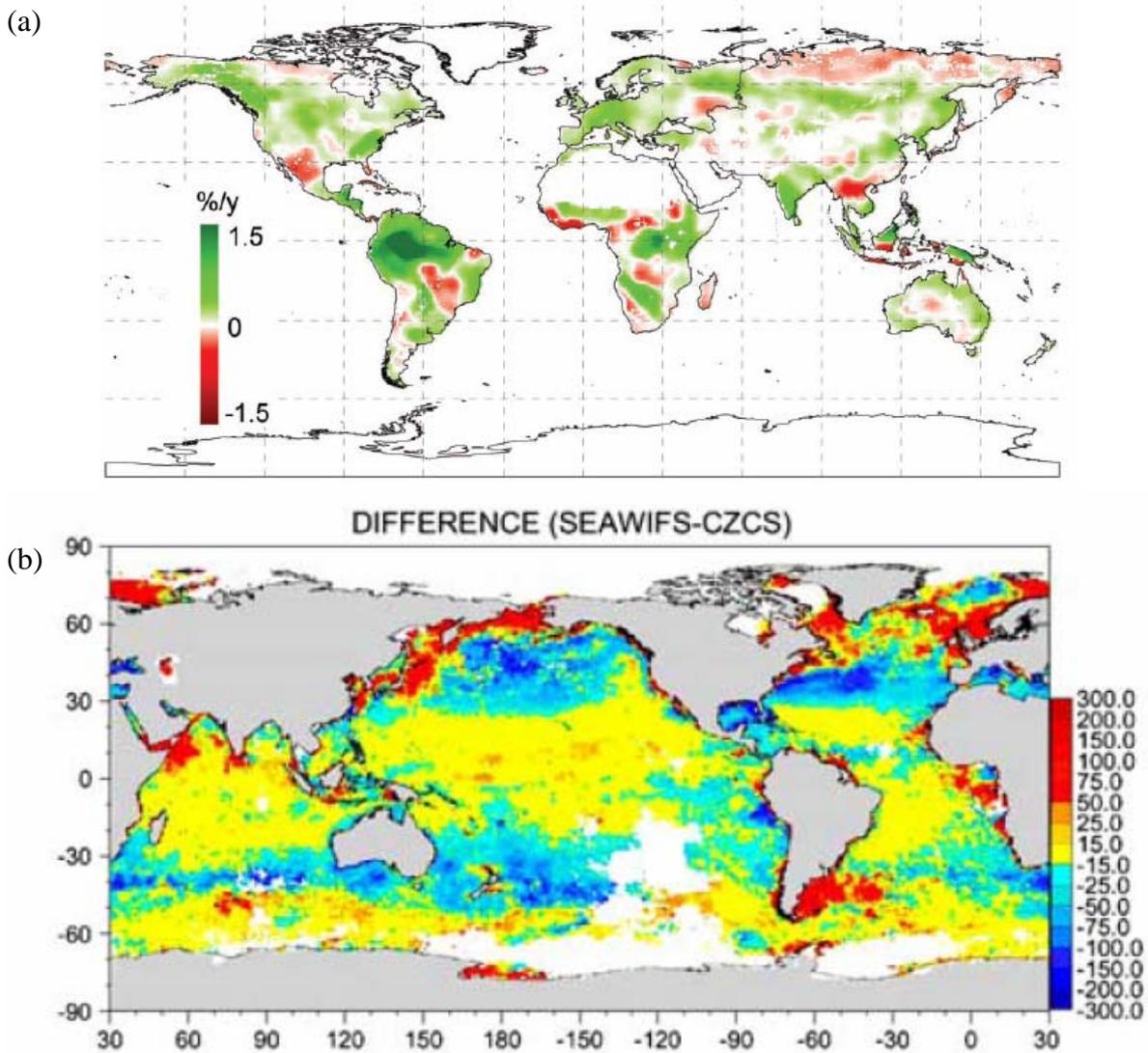
### 42 ***1.2.3 Methods and Confidence***

43  
44 Where long data series exist, detection of trends or changes in systems or sectors attributes that are  
45 beyond natural variability has most commonly been made with regression, correlation, and time-series  
46 analyses. When data exist from two (or more) discontinuous time periods, two-sample tests have  
47 frequently been employed. Testing is also done for abrupt changes and discontinuities in a data series.  
48 Regression and correlation methods are frequently used in the detection of a relationship of the  
49 observed trend with climatic variables. Methods also involve studies of process-level understanding of  
50 the observed change in relation to a given regional climate change, and the examination of alternative  
51 explanations of the observed change, such as land-use change. The analysis of process-level

1 understanding sometimes involves comparison of observations to climate-driven model simulations.

2  
3 *1.2.3.1 Statistical techniques*  
4

5 Continuous and discontinuous data series, collected or summarised on an annual basis, are typically  
6 examined for evidence of trend using statistical analysis, with calculation of a significance level,  
7 i.e., the confidence of a real trend being present rather than occurring by chance from random data.  
8 These types of studies include those reporting data on species over long periods (e.g., Abu-Asab *et al.*  
9 *et al.* 2001; Visser *et al.* 2003)), covering wide geographic areas (e.g. Menzel and Fabian 1999; Sanz  
10 2003), and spanning a number of different variables such as multi-taxa (e.g. Bradley *et al.* 1999;  
11 Ledneva *et al.* 2004). Autocorrelation in data series can be overcome by using time-series analyses  
12 that specifically take into account the dependencies between successive data values. Abrupt change  
13 in a data series can be identified by change-point analysis, including Bayesian techniques (Dose and  
14 Menzel 2004).



46 **Figure 1.1:** (a) Estimated Changes in Net Primary Productivity (1982-1999) derived from  
47 independent NDVI data sets from the Global Inventory Monitoring and Modelling Studies  
48 (GIMMS) and Pathfinder Advanced Very high Resolution Radiometer Land (PAL). (b) Global  
49 Ocean Productivity, from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) era (1997-mid  
50 2002), the Coastal Zone Colour Scanner (CZCS) era (1979-mid 1986), and the difference. White  
51 indicates missing data. Units for both are  $g C m^{-2} y^{-1}$  (Gregg *et al.* 2003; Nemani *et al.* 2003).

1 Even when data exist as a series, researchers have sometimes chosen to compare results from an  
2 early group of years with a more recent group of years, when a step change in the recorded  
3 variables may have been consistent with a step change in temperature (Fitter and Fitter 2002; Butler  
4 2003). When data do not form a series of observations but derive from two time points, typically  
5 recent and older in time, two sample comparisons as noted above may still be possible. An  
6 alternative approach is to count the number of changes in a certain direction. If no change has  
7 occurred then equal numbers of positive and negative changes would be expected.

8  
9 For evidence of climatic response, methods include (i) correlation with multiple climatic variables,  
10 (ii) examining trends through time and (iii) a comparison between two different periods in time.  
11 Some authors suggest an approach that combines empirical and process-based evidence for  
12 detecting a climate influence on living organisms (Sparks and Tryjanowski 2005). While many  
13 phenological models are based on regressing an observed phenological event against temperature  
14 measured over a fixed period, such models are unable to represent within-population variation in  
15 phenology. Gienapp (Munich Re Group 2005) have proposed a ‘proportional hazards model’ to  
16 describe phenology and illustrate it with an example from breeding time in birds.

#### 17 18 1.2.3.2 *Analysis of evidence of no change*

19  
20 In many biological field studies, species within an area are not fully surveyed, nor is species  
21 selection typically based on systematic or random sampling. Thus analyses of those species  
22 showing no change are incomplete. An exception are studies that rely on network data (an example  
23 analysis might be change in spring green-up of a number of species recorded in botanical gardens  
24 across a continent (Menzel and Fabian 1999)). Analysis of change and no-change within network  
25 data provides (1) a check on the accuracy of the use of the indicator for global warming and (2) the  
26 ability to check for ‘false positives,’ i.e., changes observed where no significant temperature change  
27 is measured. The latter can help to elucidate the role of non-climate drivers in the observed changes.

28  
29 Such tests are useful for joint attribution studies (1.4.2.3), where changes are classified into  
30 expected/unexpected direction/no change, and related to the warmer/cooler/no change of regional  
31 temperature. The accuracy rate of the indicators can also be assessed quantitatively by comparing  
32 direction and degree of change. A recent global meta-analysis of studies of one or many species  
33 exhibiting significant changes applied this approach of systematically comparing directions of species’  
34 and climate changes (Root *et al.* 2003). Comparison of degrees of change (including no change) have  
35 been performed, for example, in two large continental phenology studies for Europe, where variations  
36 in spring temperature trends were mirrored by varied advancement of different plant characteristics  
37 (Menzel *et al.* 2006) and by varied advancement of egg laying in flycatchers (Both *et al.* 2004).

38  
39 The analysis of evidence of no change is also related to the question of publication or assessment  
40 bias: Studies may be more likely to be submitted and published when a significant, directional effect  
41 is found and less likely when no changes are found, with a result that the ‘no change’ case may be  
42 underrepresented in the published literature. However, in contrast to single-species in single-location  
43 studies, multiple species in a single location and single or multiple species in larger-scale studies are  
44 less likely to focus only on species showing change. The latter studies systematically include sub-  
45 regions with no-change (e.g., no change in the number of frost days in the south-eastern USA (Feng  
46 and Hu 2004), little or no change in spring onset in continental eastern Europe (Ahas *et al.* 2002;  
47 Schleip *et al.* 2005) or sub-groups of species with no change (Butler 2003; Strode 2003)).

48  
49 The percentage of sites exhibiting ‘no change’ can be assessed by large-scale network studies (e.g.,  
50 see 1.4.1.1 Menzel *et al.* 2006), although site selection depends on network characteristics. For  
51 investigations of a suite of processes or species at numerous locations, the reported ratio of how

1 many species are changing over the total number of species rests on the assumptions that all species  
2 in the area have been examined and that species showing no change do not have a higher likelihood  
3 of being overlooked. Both multi-species network data and studies on groups of species may be used  
4 to investigate the resilience of systems and possible time-lag effects. These are important processes  
5 in the analysis of evidence of no change.  
6  
7

### 8 **1.3 Observed Changes in Systems and Sectors**

9

10 The following sections assess studies that have been published since the TAR of observed changes  
11 in the cryosphere, hydrology and water resources, coastal processes and zones, freshwater and  
12 marine biological systems, terrestrial biological systems, agriculture and forestry, human health,  
13 and disasters and hazards. In some cases, studies published before the TAR have been included,  
14 either because they have not been cited in the TAR, or because they have been considered to  
15 contain relevant information. The sections describe climate and non-climate driving forces for the  
16 system or sector, assesses the evidence regarding observed changes in key processes, highlights  
17 issues regarding the absence of observed changes and conflicting evidence, and considers how the  
18 evidence of change relates to adaptation and vulnerability.  
19  
20

#### 21 **1.3.1 Cryosphere**

22

23 The cryosphere reacts sensitively to present and past climate changes. The main components of the  
24 cryosphere are mountain glaciers and ice caps, floating ice shelves and continental ice sheets,  
25 seasonal snow cover on land, frozen ground, sea ice and lake and river ice. In Chapter 4 of WGI,  
26 the changes in the cryosphere since the TAR are described in detail, including the description of  
27 climate and non-climate forcing factors and mechanisms. Here we concentrate on the effects of  
28 recent cryospheric changes on the environment and on human activities.  
29

30 There is abundant evidence that the vast majority of the cryospheric components are undergoing  
31 generalised shrinkage in response to warming. Moreover, in several cases the shrinkage shows an  
32 accelerated trend in recent decades, consistent with the enhanced observed warming. A few cases  
33 where cryospheric components show current growth are also described (e.g., in the interior of the  
34 ice sheets and in a few maritime glaciers). Here only brief description is made of sea level rise due  
35 to cryosphere reduction. Its detailed characteristics, trends and effects are found in Section 1.3.3  
36 (Coastal processes and zones), in Chapter 6, in the regional chapters (e.g. Chapter 15), and in WGI  
37 (Chapter 4 and Chapter 5).  
38

##### 39 **1.3.1.1 Effects of changes in mountain glaciers and ice caps**

40

41 Mountain glaciers and ice caps show a generalised recession and shrinkage in response to warming,  
42 in many cases with accelerated trends in the last 2 decades (Box 1.1). In the case of the retreat of  
43 mountain glaciers and ice caps there is ample evidence suggesting that the 20<sup>th</sup> century recession is  
44 outside the range of normal climate variability of the last several millennia (e.g. Haeberli 2003; EEA  
45 2004). A few maritime glacier areas are advancing due to increased local and regional precipitation  
46 in Norway and New Zealand (Chinn *et al.* 2005), although in the last few years the mass balance of  
47 small Norwegian glaciers started diminishing, while that of larger glaciers still increases, suggesting  
48 a reversal. In southern South America, a few glaciers are also advancing, presumably related to  
49 increased precipitation, (Holmlund and Fuenzalida 1995; Skvarca and Naruse 1997; Rivera *et al.*  
50 2002). Effects of changes in mountain glaciers and ice caps have been documented, for example, in  
51 runoff, ocean freshening, sea level rise, and changing hazard conditions (Haeberli 2002).

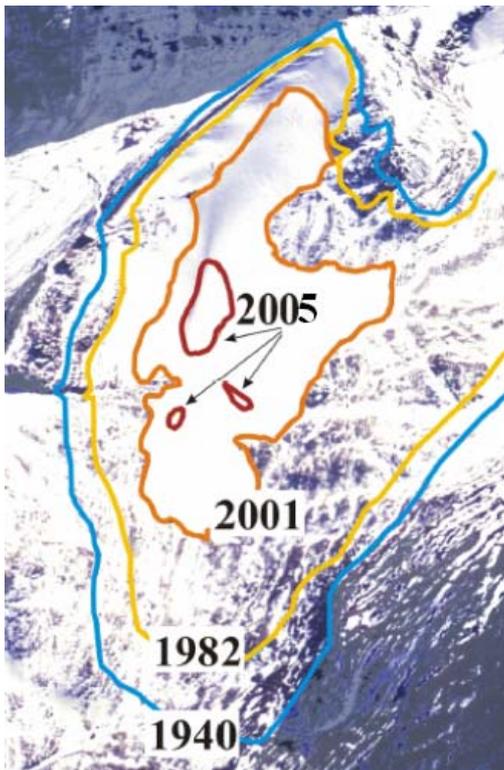
**Box 1.1: The Retreat of Chacaltaya Glacier and its Effects**

The observed general glacier retreat in the warming tropical Andes has accelerated significantly in the last decades (Coudrain *et al.* 2005). The retreat is particularly dramatic for the small-sized glaciers, such as the Chacaltaya Glacier in Bolivia (16°S), whose area in 1962 was 0.20 km<sup>2</sup>, and has reduced presently (2005) to less than 0.04 km<sup>2</sup> (Fig. 1.2) (Ramírez *et al.* 2001; Coudrain *et al.* 2005). Current estimates show that Chacaltaya Glacier may disappear completely before 2010. In the period 1992-1998 the glacier suffered the loss of 40% of its average ice thickness, and 67% of its volume, with a surface area reduction >40%. The equilibrium line altitude is located now above the upper reaches of the glacier (>5360 m), resulting in a continuous year-round exposure to ablation. About 80% of the glaciers in Bolivia have an area <0.5 km<sup>2</sup> (Jordan 1991), so a rapid shrinkage of these glaciers similar to Chacaltaya can be expected.

The link of glacier mass balance changes to meteorological conditions is more complex for tropical glaciers than for glaciers located in mid- and high-latitudes, since factors controlling albedo such as the duration of dry events, precipitation and humidity, might be equally or more important than local temperature (Sicart *et al.*, 2003). However, the fast glacier shrinkage in the tropics seems to be consistent with an upward rise of the 0°C isotherm and thus of the equilibrium line.

Ice melt from Chacaltaya Glacier, located in Choqueyapu basin, provides part of the water resources to the nearby city of La Paz, allowing release of water stored as ice throughout the long and dry winter season (April-September). Many basins in the tropical Andes have experienced an increase in runoff in recent decades, while precipitation has remained near-constant, or with a tendency to decrease (Coudrain *et al.* 2005). This short-term increase in runoff is interpreted as the consequence of glacier retreat, but in the long-term there will be a reduction in water supply as the glaciers shrink beyond a critical limit (Janssens *et al.* 2003).

Chacaltaya Glacier, with a mean altitude of 5260 m above sea level, was until very few years ago the highest skiing station in the world. After the accelerated shrinkage of the glacier during the 1990s, Bolivia lost its only ski area directly affecting the development of snow sports and recreation in this part of the Andes where glaciers are an important part of the cultural heritage



**Figure 1.2:** Areal extent of Chacaltaya Glacier from 1940 to the present. By 2005 the glacier had separated into 3 distinct areas. Adapted from (Coudrain *et al.* 2005).

1  
2 *Increased glacial runoff.* Many small glaciers in mid and low latitudes are disappearing, with  
3 consequences for water resources (e.g., in the Alps, Andes, central Asia, and the Arctic – see  
4 Chapter 4 in WGI). Increases in glacial melt lead at first to increased river runoff and discharge  
5 peaks and increased melt season (Boon 2003; Juen 2003; Hock 2005; Hock 2005), which can be  
6 sustained in the medium term (years-to-decades) depending on glacier size. In the longer range  
7 (decadal-century scale), glacier wasting is amplified by positive feedback mechanisms and glacier  
8 runoff starts decreasing (Janssens *et al.* 2003), although there is no significant evidence for this yet.  
9 Enhanced glacial melt can produce increased glacier lubrication at the bed and subsequent glacier  
10 flow acceleration, which can result in glacier creep thinning. This may be happening already for  
11 example in Patagonia and Alaska (Arendt 2002; Rignot 2005).

12  
13 *Glacier hazards.* Formation of large lakes is occurring as glaciers retreat from prominent Little Ice  
14 Age moraines, especially in the steep Himalayas (Yamada 1998; Mool *et al.* 2001; Mool *et al.*  
15 2001) and the Andes (Ames and *et al.* 1989; Kaser 2001; Kaser and Osmaston 2002). At the same  
16 time, thawing of buried ice is destabilizing these moraines. These lakes thus have a high potential  
17 for Glacier Lake Outburst Floods (GLOFs). Governmental institutions in the respective countries  
18 (Nepal, Bhutan, Peru) have provided extensive safety work and many of the lakes are now either  
19 solidly dammed or drained. It is estimated that 20 potentially dangerous glacial lakes still exist in  
20 Nepal and 24 in Bhutan (Yamada 1998), several in the Cordillera Blanca and other Peruvian  
21 Cordilleras, recommending vigilance. The temporary increase in glacier melt can also produce  
22 enhanced GLOFs, as has been reported in Chile (Peña and Escobar 1985). High-resolution satellite  
23 imagery combined with geoinformatics are increasingly used now for observing, anticipating and  
24 assessing rapidly changing hazards related to snow, glaciers and permafrost in cold mountain  
25 regions (e.g. Huggel *et al.* 2004; Huggel *et al.* 2005; Kaab *et al.* 2005).

26  
27 *Sea level rise.* Global glacier volume losses show significant acceleration since the end of 1980s  
28 (Meier *et al.* 2003), including Alaska (e.g. Arendt 2002), Patagonia ice fields (e.g. Rignot 2003),  
29 North Western USA and Canada (e.g. Bidlake *et al.* 2005), High Mountain Asia (e.g. Aizen *et al.*  
30 2006) and in the Arctic (e.g. Abdalati *et al.* 2004). For a global dataset of ~30 glaciers in 9  
31 mountain ranges, the average annual glacier thinning in 1993/2003 was ~0.75 m/y of water  
32 equivalent (w.e.), which is about three times the average thinning in the period 1980-1993 (WGMS  
33 2005). In Chapter 4, WG1, the best estimation of the contribution of glaciers and ice caps to sea  
34 level rise, including the peripheral ice masses around Greenland and Antarctica, is  $0.35 \pm 0.26$   
35 mm/yr in 1960/61-1991/1992, rising to  $0.81 \pm 0.43$  mm/yr in the period 1992/93-2002/2003  
36 (Ohmura 2004; Cogley 2005; Dyurgerov and Meier 2005). Recent sea level estimates for the ice  
37 sheets show an increased contribution in Greenland from  $0.23 \pm 0.08$  mm/year in 1996 to  $0.57 \pm 0.1$   
38 mm/year in 2005 (Rignot and Kanagaratnam 2006), and a positive overall contribution from  
39 Antarctica of  $0.4 \pm 0.2$  mm/year (Velicogna and Wahr 2006). In Chapter 5, WGI, total sea level rise  
40 reported during 1961-2003, including thermal expansion and other causes, is  $1.8 \pm 0.5$  mm yr<sup>-1</sup>,  
41 while in 1993-2003 it is  $3.1 \pm 0.8$  mm yr<sup>-1</sup> (95% confidence intervals). That is, glaciers, ice caps and  
42 ice sheets have contributed during the last decade a total of  $1.78 \pm 0.73$  mm yr<sup>-1</sup>, equivalent to  
43 ~57% of global sea level rise.

44  
45 *Impact on Earth's gravitational field and crustal uplift.* The main component of the Earth's  
46 obliquity, known as  $J_2$ , is decreasing on a secular time frame, due to tidal friction, post-glacial  
47 rebound and other causes (e.g. Munk 2002), which causes an acceleration of the Earth's rotation  
48 rate. In 1998  $J_2$  began to increase, which has been suggested to be partially due to accelerated  
49 melting of northern hemisphere mountain glaciers, ice caps and the Greenland ice sheet (Dickey  
50 2002; Ivins and Dyurgerov 2004). Recent glacier melting is also resulting in local and regional  
51 crustal uplift in Alaska and other mountain regions (Larsen 2005).

1  
2 *Obliteration of paleoclimatic records.* Stable isotope oxygen species from high altitude records in  
3 Tibet and the Andes have enriched significantly after 1800, showing that the last 50 years have  
4 been warmer than anytime during the last 1000 years. In Quelccaya Ice Cap, Peru, firn and ice  
5 melting after the 1970s has resulted in water percolation and mixing of chemical species that is  
6 destroying a valuable climate record of ~1500 years of past climate (Thompson *et al.* 2003).

7  
8 *Plant and animal colonisation.* Enhanced colonisation of plants and animals in deglaciated terrain is  
9 a direct effect of glacier and also snow retreat (e.g. Jones 2003). Although changes due to other  
10 causes such as introduction by human activities, increased UV radiation, contaminants and habitat  
11 loss might be important (e.g. Frenot *et al.* 2005), a widespread “greening” has been reported in  
12 relation to warming in the Arctic and also in the Antarctic Peninsula, which is discussed in more  
13 detail in 1.3.5.

14  
15 *Landscape alteration, tourism and mountain sports.* Glacier retreat causes striking changes in the  
16 landscape, which has affected living conditions and local tourism in many mountain regions around  
17 the world (Watson and Haeberli 2004; Mölg *et al.* 2005). A loss of ice climbs and associated  
18 reduction in sport has been reported in several mountain ranges in the Andes and the Alps, and in  
19 Africa (Bowen 2002).

#### 20 21 *1.3.1.2 Effects of changes in ice shelves*

22  
23 The ice shelves of the Antarctic Peninsula and in the Canadian Arctic, most of which are several  
24 thousand years old, are not just retreating but are also undergoing rapid collapse (Scambos 2004)  
25 and (Mueller *et al.* 2003) in response to regional warming. Because they are already floating,  
26 melting of ice shelves does not contribute to sea level rise. However, the collapse of ice shelves has  
27 resulted in many cases in significant flow acceleration of inland glaciers (Scambos 2004) which can  
28 contribute to sea level rise.

#### 29 30 *1.3.1.3 Effects of changes in ice sheets*

31  
32 There is evidence for increased snow accumulation in both the interior of Greenland (Johannessen  
33 *et al.* 2005) and East Antarctica (Davis *et al.* 2005). In spite of this increased accumulation,  
34 Greenland is overall losing mass due to glacier flow acceleration (Rignot and Kanagaratnam 2006)  
35 and peripheral thinning (Krabill *et al.* 2004). A large part of West Antarctica in the Amundsen Sea  
36 sector is rapidly losing mass (Thomas *et al.* 2004), and there is recent evidence that a significant  
37 mass reduction of the Antarctic ice sheet is occurring, largely as a result of thinning and  
38 acceleration near the coast, with a major contribution from West Antarctica (Velicogna and Wahr  
39 2006). Sea level rise estimates for the ice sheets are summarised in section 1.3.1.1. The enhanced  
40 flow of the ice streams and glacier systems in Greenland and Antarctica is most probably a result of  
41 a combination of the collapse of their respective ice shelves and increased basal water lubrication  
42 (Zwally *et al.* 2002; Thomas *et al.* 2003; Rignot *et al.* 2004; Rignot and Kanagaratnam 2006). This  
43 can result in increased production of iceberg calving, which can in turn affect sea navigation,  
44 although no clear evidence for this exists yet.

#### 45 46 *1.3.1.4 Effects of changes in snow cover*

47  
48 There is a general worldwide decrease in recent decades of snow cover extent in spring, which is  
49 well reported for the Northern Hemisphere, including western North America (Armstrong and  
50 Brodzik 2001), Eurasia (Ueda 2003) and the Alps (Laternser and Schneebeli 2003). Snow-cover  
51 depth in western North America also shows a spring reduction at 75% of the sites measured since

1 1950 (Mote *et al.* 2005). There are a few high- latitude areas, such as Finland and the former Soviet  
2 Union, where increases in winter precipitation have resulted in a larger snow-cover extent in mid-  
3 winter (Kitaev *et al.* 2002; Hyvarinen 2003). In the Southern Hemisphere, a substantial decline in  
4 snow cover and snow depth has been measured in Australia, particularly in spring (Nicholls 2005),  
5 and an increase in the zero-degree isotherm altitude has been reported in central Chile, which is  
6 thought to have resulted in a corresponding snowline rise (Carrasco *et al.* 2005).

7  
8 *Earlier snow melt.* A direct consequence of the reduced snow cover is that spring peak river flows  
9 are occurring earlier, which is well reported for Western United States (Cayan 2001; Regonda *et al.*  
10 2005), for western North America in general (Stewart *et al.* 2005), Alaska (Stone *et al.* 2002;  
11 Hodgkins *et al.* 2003), central Canada (Dery and Wood 2005), and northern Eurasia (Yang *et al.*  
12 2002; Ye and Ellison 2003). There is also evidence for increase of winter base flow in northern  
13 Eurasia and North America (e.g. Yang *et al.* 2002). More detailed references are presented in  
14 section 1.3.2.

15  
16 *Ski areas.* There is a measured trend towards less snow at low altitudes which is affecting ski areas,  
17 including the Alps of Switzerland and Austria, (Breiling 1998; Elsasser and Messerli 2001; Steininger  
18 *et al.* 2002; Beniston 2003; Beniston 2004), the eastern US (Hamilton *et al.* 2003), southern Canada  
19 (Scott *et al.* 2003), Australia (Nicholls 2005) and central Chile (Casassa *et al.* 2003).

#### 20 21 1.3.1.5 Effects of changes in frozen ground

22  
23 Frozen ground includes permafrost, near-surface soil affected by short-term freeze-thaw cycles, and  
24 seasonally frozen ground. Permafrost shows a general warming trend and degradation (i.e., decrease  
25 in thickness and areal extent) during the last century (Romanovsky 2002; Harris 2003), mainly in  
26 response to climate warming, in many cases with evidence for acceleration (Camill 2005). Strong  
27 evidence for this warming is provided by temperature increase in deep borehole records in the  
28 Northern Hemisphere (Chapter 4, WGI). The active layer, that is, the ground above permafrost that  
29 seasonally thaws and freezes, has shown a significant thickening in many regions (Frauenfeld  
30 2004). Large degradation has been detected in permafrost in Alaska since 1982, in areas that have  
31 been previously stable for thousands of years (Jorgenson *et al.* 2006). In areas with no permafrost,  
32 the thickness of seasonally frozen ground has decreased in many regions of northern Russia  
33 (Frauenfeld 2004). In the Southern Hemisphere no conclusive data are yet available.

34  
35 *Impacts on surface runoff.* Degradation of seasonally frozen ground and permafrost and increase in  
36 active-layer thickness should result in increased importance of surface water (for example, in  
37 wetlands and pond formation in thermokarst and groundwater in the local water balance  
38 (McNamara *et al.* 1999), as has been detected in Alaska (Yoshikawa and Hinzman 2003), and in  
39 Siberia (Smith *et al.* 2005). Thickening of the active layer is thought to be partly responsible for  
40 increased river runoff in central Asia (Zhang *et al.* 2004). More details are presented in 1.3.2.

41  
42 *Vegetation and wetland changes.* Permafrost and frozen ground degradation are resulting in an  
43 increased areal extent of wetlands in the Arctic, with an associated “greening”, i.e. plant  
44 colonization (see 1.3.1.1 and 1.3.5). Wetland increase might produce increased release of carbon to  
45 the atmosphere in the future (e.g. Lawrence and Slater 2005), but this has not been documented.  
46 Wetland changes also affect the fauna (refer to 1.3.5).

47  
48 *Infrastructure damage.* Permafrost warming and degradation together with an increasing depth of  
49 the active layer cause mechanical weakening of the ground, and ground subsidence and formation  
50 of thermokarst have a weakening effect on existing infrastructure such as buildings, roads, airfields  
51 and pipelines (Couture 2000; Nelson 2003). There is significant evidence of structures in North

1 America and Siberia that have already been affected by thawing, for example in Alaska (USARC  
2 2003), in Canada (e.g. Allard *et al.* 2002), and in Russia (e.g. Nelson *et al.* 2002) although in a few  
3 cases at least part of the thawing may be attributed to urbanization and heat-island effects  
4 (Tutubalina and Ree 2001; Hinkel *et al.* 2003). Permafrost melting has also produced increased  
5 coastal erosion in the Arctic (e.g. Beaulieu and Allard 2003). This is described in detailed in section  
6 1.3.3.

7  
8 *Slope stability problems.* Thawing and deepening of the active layer in high-mountain areas can  
9 produce slope instability and rock falls (Watson and Haerberli 2004), which in turn can trigger  
10 outburst floods. A reported case is the exceptional rock fall activity in the Alps during the 2003  
11 summer heat wave, when the active layer in the Alps deepened significantly, from 30% to 100% of  
12 the depth measured before the heat wave (Noetzi J. 2003; Gruber *et al.* 2004; Schar *et al.* 2004). In  
13 the Andes, rockfall activity has occasionally triggered outburst floods (Casassa 1993; Carey in  
14 press), but there is no evidence of increased activity in the last few decades.

#### 15 1.3.1.6 Effects of changes in sea-ice

16  
17  
18 Arctic sea ice has reduced significantly in the last few decades, with a decline of ~3% per decade in  
19 the annual mean extent since 1978 (Comiso 2003), which is consistent with the observed  
20 atmospheric warming. In the Antarctic as a whole, although there are regional variations, with some  
21 regions showing reductions, sea-ice coverage has increased somewhat since the late 1970s,  
22 although at a much lesser rate than the Arctic sea-ice reduction (Comiso 2003).

23  
24 Reduced sea ice will probably result in increased navigation and possibly a rise in offshore oil  
25 operations (ACIA 2004), but there are no quantitative data to support this. Geopolitical interest in  
26 the Arctic Ocean has increased in recent years as a result of sea ice reduction and increased  
27 shipping access, as is the case for example of the Danish and Canadian territorial claims over Hans  
28 Island in Nares Strait, off the north-western coast of Greenland. Together with the reduction in sea  
29 ice, previously uncharted islands have been discovered (Mohr and Forsberg 2002), which can be  
30 relevant for territorial and ocean claims.

31  
32 *Ecosystem impacts.* There are several changes in the polar marine ecosystems which have been  
33 related to reduction of sea ice and ocean freshening. For example, a reduction of krill biomass and  
34 increase in salps has been reported near the Antarctic Peninsula region and linked with sea ice  
35 reduction (Loeb *et al.* 1997; Atkinson 2004). In the Arctic, marine algae have died in the period  
36 1970-late 1990s and have been replaced by less productive algae species usually associated with  
37 freshwater (ACIA 2004). There are also impacts on Arctic mammals (ACIA 2004). More detailed  
38 description of impacts is given in Section 1.3.4.5.

39  
40 *Ocean freshening and circulation.* There is some evidence for freshening of North Atlantic waters  
41 (Curry *et al.* 2003; Curry and Mauritzen 2005), which is probably a combination of reduced sea-ice  
42 formation and sea-ice melting, glacier, ice sheet and ice shelf melt, increased precipitation, and  
43 increased river runoff to the Arctic ocean (Dickson *et al.* 2002). In the Ross Sea there is also  
44 evidence for freshening (Jacobs *et al.* 2002). The Atlantic meridional overturning circulation  
45 (MOC) has weakened by ~30% in 1985-1995 (Bryden *et al.* 2005), which also suggests that a  
46 reduced thermohaline circulation (THC) is occurring in the North Atlantic. This in turn may imply a  
47 reduced inflow of warm Atlantic water to the Nordic seas, which could result in colder climate in  
48 the North Atlantic. However, the slow-down of the THC might also be expected to give rise to an  
49 increase in salinity difference, thus enhancing the THC (Wu *et al.* 2004).

#### 50 51 1.3.1.7 Effects of changes in lake and river ice

1  
2 Seasonal variations in lake and river ice are relevant in terms of freshwater hydrology, freshwater  
3 ecosystems and human activities such as ice skating, winter transportation, bridge and pipeline  
4 crossings. In addition to the forcing caused by temperature changes, lake and river ice is very  
5 sensitive to changes in snow cover which acts as a natural thermal insulator. There is abundant  
6 evidence for a spatial reduction of lake and river ice for North America and Siberia (Prowse 2002;  
7 ACIA 2004).

8  
9 The freezing season of lakes and rivers has been reduced by one to three weeks in the Arctic over  
10 the past 100 years (ACIA 2004), with evidence of earlier timing of freshwater ice break-up (Bonsal  
11 and Prowse 2003). In the Southern Hemisphere there is some historical knowledge of reduction of  
12 lake ice, but there is a lack of scientific evidence. Over the last 150 years, spring breakup dates for  
13 large lakes and rivers in North America, Europe, and Asia are around 10 days earlier and freeze  
14 dates are around 9 days later, with reduced thickness and areal ice cover (Schindler *et al.* 1990;  
15 Magnuson *et al.* 2000; Hodgkins *et al.* 2002; Yoo and D'Odorico 2002; Assel *et al.* 2003;  
16 Huntington *et al.* 2003; Todd and Mackay 2003; Hodgkins *et al.* 2005; Schindler *et al.* 2005).

17  
18 *Impacts due to changes in lake ice and river ice.* Lake thermal structure and quality/quantity of  
19 under-ice habitation lakes have been reported, as well as changes in suspended particles and  
20 chemical composition (Wrona 2005). Changes in earlier ice-out date have been reported which can  
21 have relevant effects on lake ecology, such as summer oxygen depletion rate (Stewart 1976),  
22 abundance and productivity of phytoplankton (Maeda and Ichimura 1973), and organisms at higher  
23 trophic levels (Porter *et al.* 1996). In rivers, earlier and more intense melt conditions can result in  
24 significant breakup events due to ice jamming, which can, in turn, result in severe flooding (Prowse  
25 2002), but there is a lack of scientific evidence that this is already happening. Changes in river ice  
26 dynamics may have ecological effects on aquatic biota (Scrimgeour *et al.* 1994) and on riparian  
27 vegetation (Prowse 2002). More detailed discussions are presented in 1.3.2 and 1.3.4.

28  
29 *1.3.1.8 Evidence of adaptation and vulnerability in the cryosphere*

30  
31 Modes of human response to climate change, including warming, are just beginning to be  
32 systematically documented in the cryosphere (MacDonald *et al.* 1997; Krupnik and Dyanna 2002;  
33 Huntington and Fox 2004). The impacts associated with these changes are both positive and  
34 negative, and are most pronounced in relation to the migration patterns, health, and range of  
35 animals, plants and birds that indigenous groups depend on for their livelihood and cultural identity.  
36 Responses vary by community and are dictated by particular histories, perceptions of change and  
37 the viability of options available to groups (Ford and Smit 2004; Helander and Mustonen 2004). In  
38 Sachs Harbor, Canada, responses include individual adjustments to the timing, location and  
39 methods of harvesting animals as well as adjusting the overall mix of animals harvested to  
40 minimize risk (Berkes and Jolly 2002). Communities particularly vulnerable to coastal erosion such  
41 as Shishmerf, Alaska, are faced with relocation. Many communities in the north are stepping up  
42 monitoring efforts to watch for signs of change so they can respond accordingly in both the long  
43 and short term (Fox 2002). The International Polar Year (2007-2009) is designed to help coordinate  
44 and facilitate these monitoring efforts on a circumpolar scale. The use of new GPS technologies are  
45 helping some hunters manage the dangers of sea ice travel while leaving others to assume more risk  
46 without adequate experiential knowledge (George *et al.* 2004; Aporta and Higgs 2005). Agent-base  
47 simulation models are also being developed to assess adaptation and sustainability in small-scale  
48 Arctic communities (Berman *et al.* 2004). Effective responses will be governed by increased  
49 collaboration between indigenous groups, climate scientists, and resource managers (Huntington  
50 and Fox 2004).

51

### 1.3.1.9 Summary

There is abundant evidence that most of the cryospheric components in polar regions and in mountain areas are undergoing generalised shrinkage in response to warming, although there are a few cases of both shrinkage and growth related mainly to changes in precipitation. The observed impacts of cryosphere reduction include snowmelt advance and increased winter base flow due to enhanced snow melt; formation of thermokarst terrain and disappearance of surface lakes in thawing permafrost; infrastructure damage in regions under permafrost degradation; enhanced glacier hazards and slope instability due to mechanical weakening driven by ice and permafrost melting; regional ocean freshening and changes in thermohaline circulation which are probably related to the freshening; sea level rise due to ice mass reduction; biotic colonization and faunal changes in deglaciated terrain; changes in lacustrine and marine ecosystems affected by lake-ice and sea-ice reduction; changes in living conditions and reduced outdoor and tourism activities related to skiing; ice climbing and scenic activities in cryospheric areas affected by degradation; and indigenous livelihoods in the Arctic. Responses to climate change, including warming, vary by community and are beginning to be systematically documented.

### 1.3.2 Hydrology and water resources

This section focuses on the relationships of runoff, lake levels, groundwater, floods and droughts, and water quality with observed climate variability, climate trends, and land-use and land-cover changes reported since the TAR. The time period of consideration is 1970-2005, with many studies extending to earlier decades. Both climate and non-climate factors influence the hydrological cycle and in turn influence surface and groundwater water resources. Climate variables important for surface and groundwater systems are precipitation, temperature and evaporation. These variables are often influenced at regional scales by larger-scale atmosphere circulations associated with ENSO, NAO, and other patterns of variability that operate at within-decadal and multi-decadal timescales (Chapter 3 WGI). Non-climatic factors important for changes in hydrological variables are human interventions in water catchments, such as land-use and land-cover changes, and changes in rates of water consumption for agricultural, industrial, commercial, and domestic uses. These in turn affect evaporation and transpiration, soil moisture storage, infiltration and percolation into soil and groundwater, as well as runoff quantity and timing, and water quality.

#### 1.3.2.1 Changes in surface water and groundwater systems

An increasing trend in average annual runoff in large basins in the Eurasian Arctic has been related to permafrost melting (Peterson *et al.* 2002). One global study found that continental river runoff has increased in the 20<sup>th</sup> century, and attributes this to both climate warming and the effect of increased atmospheric carbon dioxide, the latter resulting in decrease of plant transpiration and increase in runoff (Gedney *et al.* 2006). However, other evidence for such a CO<sub>2</sub>-runoff relationship is difficult to find. There is abundant evidence of the earlier occurrence of spring peak river flows and an increase in winter base flow in North America and northern Eurasia, in agreement with local and regional climate warming in those areas (Table 1.2a). These have been related to both NAO changes and climate trends and agree both with recent regional rainfall increments and also a reported increase in permafrost melting. The early spring shift in runoff leads to a shift in peak river runoff away from summer and autumn, which are normally the seasons with highest water demand, resulting in possible consequences for future water availability (see WGII Chapter 3).

A key determinant of annual runoff is the relationship between changes in annual precipitation and evapotranspiration. A decreasing trend in pan evaporation (ETpan) over the past 50 years has been

1 observed in many countries (Chattopadhyay and Hulme 1997; Golubev *et al.* 2001; Roderick and  
 2 Farquhar 2002; Roderick and Farquhar 2004; Tebakari *et al.* 2005). In contrast, a recent  
 3 reassessment of evaporation data from the United States (Walter *et al.* 2004) and the former Soviet  
 4 Union (Golubev *et al.* 2001) suggests an increasing trend in actual evaporation (ET) during the last  
 5 forty years in spite of decreases in ETpan. In most, but not all, regions the net result has been an  
 6 increase in ET but a decrease in ETpan (Chapter 3 WGI). Differences in interpretation regarding the  
 7 “pan evaporation paradox” depend on differences in regional climates and methodologies, as well  
 8 as on limited observations (Chattopadhyay and Hulme 1997; Milly *et al.* 2002; Roderick and  
 9 Farquhar 2004; Walter *et al.* 2004; Tebakari *et al.* 2005; Gedney *et al.* 2006). It can be concluded  
 10 that no significant trends in ET can be detected globally.

11  
 12 **Groundwater.** Groundwater in shallow aquifers is linked to the hydrological cycle and is affected  
 13 by climate variability and change through recharge processes, as well as by human interventions in  
 14 many locations. Over the last 20 years in some but not all areas of drying, groundwater water levels  
 15 have been dropping in aquifers (Chen *et al.* 2002; Ferguson and George 2003). In some regions,  
 16 such as the North China Plains, the combination of intensive pumping for irrigation and several  
 17 years of below-normal precipitation and rising temperature since the 1980s accelerated the  
 18 downward trend in water levels and has caused groundwater depression, land subsidence,  
 19 disappearance of wetlands, and intrusion of seawater in coastal zone (Zhang 2001).

20  
 21 **Lakes.** At present, no globally consistent trend in lake levels has been found (Table 1.2b). While  
 22 some lake levels have risen in Mongolia and China (Xinjiang) in response to increased snow and  
 23 ice melt, other lake levels in China (Qinghai), Australia, Africa (Zimbabwe, Zambia, and Malawi),  
 24 North America (North Dakota), and Europe (Central Italy) have declined due to the combined  
 25 effects of drought, warming and human activities. Within permafrost areas in the Arctic, recent  
 26 warming has resulted in the temporary formation of lakes due to the onset of melting, which then  
 27 drain rapidly due to permafrost degradation (e.g. Smith *et al.* 2005). A similar effect has been  
 28 reported for a lake formed over an Arctic ice shelf (i.e., an epishelf lake), which disappeared when  
 29 the ice shelf collapsed (Mueller *et al.* 2003). Permafrost and epishelf lakes are treated in detail in  
 30 Section 1.3.1.

31  
 32 **Table 1.2: Observed changes in (a) runoff/streamflow; (b) lake levels.**

33 (a) Runoff/streamflow

Location	Time period	Observed change	Author
Arctic Ocean	1936-2002	Increasing annual discharge from six largest Eurasian river to Arctic Ocean by 7% due to NAO and warming climate	(Peterson <i>et al.</i> 2002; Shiklomanov 2003)
Northern Eurasia	Last 15-20 years	Increasing annual runoff (5%) due to snow and ice melt	(Lammers <i>et al.</i> 2001; Frenkel 2004; Vishnevsky and Kosovets 2004)
Arctic Drainage: Ob, Lena, Yenisey, Mackenzie watersheds	1935-1999	Significant increase (25-90%) in winter season streamflow and decrease in river ice thickness due to warmer winter, melt of ground ice and thawing permafrost	(Serreze <i>et al.</i> 2002; Yang <i>et al.</i> 2002)
United States	1939-2002	Increase in annual runoff 26% due to increase in precipitation 7%	(Lins and Slack 1999; Parel 2004; Walter <i>et al.</i> 2004; Milly <i>et al.</i> 2005)
La Plata, Paraná and	Last 30 years	Increased streamflow 20% in	(Berri <i>et al.</i> 2002; Barros

Uruguay basins in South-eastern South America		accordance with increased rainfall 10% due to ENSO effects	<i>et al.</i> 2004)
Sweden	1807-2002	No trend in runoff due to increasing temperature offsetting the increasing precipitation	(Lindstrom and Bergstrom 2004)
United Kingdom	Last 50 years	No trend in annual runoff	(Hannaford and Marsh 2005)
Southern British Columbia and Yukon Territory Canada	1947-1996	Decreasing annual runoff (14.9%) due to temperature rise under no change in precipitation	(Zhang <i>et al.</i> 2001)
North America	1910-2002	Decline in annual discharge (0.22%/year-0.5%/year) for 31 rivers to Pacific, Arctic and Atlantic Oceans associated with decreased precipitation, increased evaporation and PDO effects	(Stewart <i>et al.</i> 2005)
Heihe and Yellow River China	1950-2000	Annual runoff decreased ~25%, rainfall decreased ~10%, temperature increase 1.2 <sup>0</sup> C in Heihe; decline in annual flux of Yellow river into sea due to decreased rainfall (41.3%), temperature increase (11.4%), increased water diversion and consumption (40.8 %), erosion and sedimentation 6.5%	(Liu and Liu 2004; Jiongxin 2005)
Southwest Australia	Last 50 years	Significant drop in annual inflow to reservoirs by 5% due to decline in May-July rainfall	(IOCI 2002)
Alaska, Western, and New England, US; Canada; northern Eurasia	1936-2000	Shift in peak streamflow 1-2 weeks due to earlier snowmelt	(Cayan 2001); (Regonda 2005), (Hodgkins <i>et al.</i> 2003), (Stewart <i>et al.</i> 2005), (Stone <i>et al.</i> 2002), (Hodgkins <i>et al.</i> 2003), (Dery and Wood 2005), (Ye and Ellison 2003), (Yang <i>et al.</i> 2002)

1

2

## (b) Lake levels

Lake Hovsgol, Mongolia	1970-2000	Rise in water level 9.22m due to increased glacier or permafrost melting	(Kumagai <i>et al.</i> 2003)
Bosten Lake Xinjiang China	1980-2000	Rise in lake level ~4m due to increasing precipitation and snow - ice melt flow from $3.08 \times 10^8 \text{m}^3$ to $9.6 \times 10^8 \text{m}^3$	(Yuan <i>et al.</i> 2003)
Qinghai Lake, China	1975-2000	Lake area decreased 149.6 km <sup>2</sup> due to combination effect of drought and human activities	(Feng and Dingbo 2003)
Daihai Lake, China	1700-1996	From 1960-1996 Lake level decreased 3.85m due to combination effects from drought and human	(Zhang and Ruijin 2001)

		activities	
Three closed lakes, Australia	c1840-1990	Decreasing lake levels 5-15m due to decrease in P/E from 0.94-0.96 to 0.79	(Jones <i>et al.</i> 2001)
Lake Chad, Africa	1953-1994	Decline in lake level and area from 25,000 km <sup>2</sup> to 1350 km <sup>2</sup> due to continued decrease in precipitation and increased water losses from increase in irrigated agriculture	(Coe 2001)
Devils Lake, North Dakota; Lake Kariba, Zimbabwe and Zambia; Lake Chilwa, Malawi	1970-2000	Lake level dropped 10-12m, and almost drying out due to decreased water inflow and increased evaporation	(Covich <i>et al.</i> 1997; Robarts <i>et al.</i> 2007)
Lakes, Central Italy	Last 20 years	Decline in lake level due to rainfall decrease and water withdrawal	(Capelli and Mazza 2005)

1

2

3 *1.3.2.2 Changes in floods and droughts*

4

5 Documented trends in floods (frequency of floods, highest flow quantiles and annual maximum  
6 daily streamflow), and droughts (low river flows and annual minimum daily streamflow) show that  
7 dry areas are tending to become drier and are expanding, while in wetter areas there is no consistent  
8 pattern of trends (Table 1.3a and b). These changes indicate that there is an ongoing intensification  
9 of the water cycle over the past 50 years at regional to continental scales (Huntington 2005).  
10 Globally, very dry areas (PDSI<-3.0) have more than doubled since the 1970s due to a combination  
11 of ENSO events and surface warming, while very wet areas (PDSI>+3.0) declined by ~5%, with  
12 precipitation as the major contributing factor during the early 1980s and temperature more  
13 important thereafter (Dai 2004). The main area where a significant drying trend has been reported  
14 is the Sahel region of Africa. The areas of increasing wetness include the Northern Hemisphere  
15 high latitudes and equatorial regions. However, the use of the Palmer Drought Severity Index is  
16 limited by its lack of effectiveness in tropical regions. Discrepancies in results for hydrological  
17 extreme events related to global warming are related to differences in record lengths (Vogel *et al.*  
18 2001; Mudelsee *et al.* 2003) and methodologies (Douglas 2000; McCabe and Wolock 2002;  
19 Pekarova 2003). Although major floods have occurred in the last few decades, no significant  
20 trends were found for flood events.

21

22

23 **Table 1.3a: Floods**

Location	Time period	Observed change	Author
Global	1865-1999	Increase in frequency of floods with discharges exceeding 100 year levels from 29 large river basins more than 200,000km <sup>2</sup>	(Milly <i>et al.</i> 2002)
Elbe and Dresden, Germany	1997-2002	Catastrophic events much larger than 100-year flood	(Becker and Grunewald 2003; Kundzewicz <i>et al.</i> 2005)
Russian Arctic rivers	Last years	Increasing catastrophic floods of frequency (0.5-1%) due to earlier breakup of river-ice and heavy rain	(Smith 2000; Buzin 2004; Frolov 2005)

Bangladesh	1980s-1998	>50-to-100-year floods from strong monsoons	(Chowdhury and Ward 2003)
Yangtze River, China	1990-1999	>50-year floods due to El Niño events	(Qian and Zhu 2001)
United States	1874-1998	No significant upward or downward trend in record-breaking floods	(Vogel <i>et al.</i> 2001)
Central Europe	1852-2002	No evidence for widespread increase in summer floods	(Mudelsee <i>et al.</i> 2003; Kundzewicz <i>et al.</i> 2005)
Southern Canada	1847-1996	Decreasing annual maximum daily streamflow 28.6% due to temperature rise with no change in precipitation	(Zhang <i>et al.</i> 2001)

1  
2**Table 1.3b: Droughts**

Location	Time period	Observed change	Author
Western two-thirds of Canada	1940-2002	Warm ENSO events lead to summer droughts	(Shabbar 2004)
Western United States.	1998-2004	One of the longest droughts in the last 105 years due to dry and unusually warm summers related to warming of western tropical Pacific and Indian Oceans	(Andreadis <i>et al.</i> 2005; Pagano 2005)
Niger and Senegal, Blue and White Nile, Congo Rivers, Africa	1950-1995	Decreasing trend in flow and high interannual variability of river flows associated with ENSO	(Jury <i>et al.</i> 2003; Conway <i>et al.</i> 2005)
Much of Europe and UK	1911-1995	No evidence of significant increase in droughts (defined as streamflow below a certain threshold)	(Hisdal <i>et al.</i> 2001; Hannaford and Marsh 2005; Hodgkins <i>et al.</i> 2005; Schrier Van der and et al 2005)
Eastern United States	1941-1999	Significant increase in annual minimum (202 out of 395 sites) and median (219 sites) daily streamflow around 1970 as a step change related to precipitation increase and NAO	(Groisman 2004; Douglas 2000; McCabe 2002)

3  
4  
5  
6  
7  
8  
9

### 1.3.2.3 Changes in thermal structure and water quality

There have been many observed changes in water quality related to thermal and chemical properties that have been attributed to warming (Gerten and Adrian.R. 2002) (Tables 1.3c and 1.7).

*Thermal Structure.* Higher water temperatures and shorter periods of ice-cover (see 1.3.1.7) and stagnation were common trends for lakes across the hemisphere in response to warmer conditions. Phytoplankton dynamics and primary productivity have also been altered in conjunction with changes in lake physics (see 1.3.4.4). Since the 1960s, surface water temperatures have warmed by 0.2 to 2°C in lakes and rivers in Europe, North America, and Asia. Along with warming surface waters, deep water temperatures (which reflect long-term trends) of the large East African lakes (Edward, Albert, Kivu, Victoria, Tanganyika, Malawi) have warmed by 0.2 to 0.7°C since the early 1900s. Increased water temperature and longer ice-free seasons influence thermal stratification and

1 internal hydrodynamics of lakes. In warmer years, epilimnetic water temperatures are higher,  
 2 evaporative water loss increases, summer stratification occurs earlier in the season, and  
 3 thermoclines become shallower. In several lakes in Europe and North America, the stratified period  
 4 has advanced by up to 20 days and lengthened by 2-3 weeks, with increased thermal stability.

5  
 6 *Chemistry.* Increased stratification reduces water movement across the thermocline, inhibiting  
 7 upwelling and mixing that provide essential nutrients to the food web. There have been decreases in  
 8 nutrients in the surface water and corresponding increases in deep water concentrations of European  
 9 and East African lakes because of reduced upwelling due to greater thermal stability. Many lakes  
 10 and rivers have increased concentrations of sulphate, base cations, silica, alkalinity, and  
 11 conductivity related to increased weathering of silicates, calcium and magnesium sulphates, or  
 12 carbonates in their catchment. In contrast, when warmer temperatures enhanced vegetative growth  
 13 and soil development in some high alpine ecosystems, alkalinity decreased because of increased  
 14 organic acid inputs (Karst-Riddoch *et al.* 2005). Glacial melting increased the input of  
 15 organochlorines (that had been atmospherically transported to and stored in the glacier) to a sub-  
 16 alpine lake in Canada (Blais *et al.* 2001).

17  
 18 Increased temperature also affects in-lake chemical processes. There have been decreases in  
 19 dissolved inorganic nitrogen from greater phytoplankton productivity (Sommaruga-Wogratz *et al.*  
 20 1997; Rogora 2003) and greater in-lake alkalinity generation and increases in pH in soft water lakes  
 21 (Psenner and Schmidt 1992). Decreased solubility from higher temperatures significantly  
 22 contributed to 11-13% of the decrease in aluminium concentration (Vesely *et al.* 2003), whereas  
 23 lakes that had warmer water temperatures had increased mercury methylation and higher mercury  
 24 levels in fish (Bodaly *et al.* 1993). A decrease in silicon content related to regional warming has  
 25 been documented in Lake Baikal Russia. River water quality data from 27 rivers in Japan also  
 26 suggest a deterioration of both chemical and biological features due to increase in air temperature  
 27 (Table 1.3c).

28  
 29  
 30 **Table 1.3c: Water quality**

Location	Time period	Observed change	Author
Lakes in Europe and North America	Recent decades	Higher lake temperatures, shorter periods with ice cover, shorter stagnation periods, altered phytoplankton dynamics and primary productivity	(Gerten and Adrian 2002)
64 studied lakes/rivers in Europe, North America and Asia	Last 40 years	Surface water temperature warming by 0.2-1.5C for 17 lakes. Stratified period has advanced by up to 20 days and lengthened by 2-3 weeks with increased thermal stability.	(Adrian and Deneke 1996; King <i>et al.</i> 1998; Livingstone and Dokulil 2001; Carvalho and Kirika 2003; Livingstone 2003; Straile <i>et al.</i> 2003; Arhonditsis <i>et al.</i> 2004; Dabrowski <i>et al.</i> 2004; Winder and Schindler 2004)
6 studied lakes in East Africa	1939-2000	Long-term temperature increase 0.2-0.7°C in deep water below 300m due to reduction of cold-water deep convection associated with milder winters	(Hecky 1994; O'Reilly 2003; Verburg 2003; Lorke 2004; Vollmer 2005)
8 studied lakes/rivers in North America, Europe, East	1991-2003 1939-2000	Decreases in nutrients in surface water and corresponding increases in deep-water concentration because of reduced upwelling due to greater	(Hambricht <i>et al.</i> 1994; Adrian and Deneke 1996; Straile <i>et al.</i> 2003; O'Reilly 2006)

Africa		thermal stability	
88 studied lakes /rivers in North America, Europe	Last 10 to 20 years	Increased catchment weathering or internal processing	(Psenner and Schmidt 1992; Bodaly <i>et al.</i> 1993; Sommaruga-Wogratz <i>et al.</i> 1997; Blais <i>et al.</i> 2001; Rogora 2003; Vesely <i>et al.</i> 2003; Worrall <i>et al.</i> 2003; Karst-Riddoch <i>et al.</i> 2005)
Lake Baikal, Russia	Recent decades	Decrease in silicon content of 30% related to regional warming	(Shimaraev <i>et al.</i> 2004)
27 rivers, Japan	Last decades	Increase in biological oxygen demand and suspended solids, and decrease in dissolved oxygen due to increase in air temperature	(Ozaki <i>et al.</i> 2003)

1

2

3 **1.3.2.4 Summary**

4

5 Changes runoff and streamflow, as well as in droughts and floods, indicate that there is an ongoing  
6 intensification of the water cycle over the past 50 years at regional to continental scales due to  
7 warming. Significant trends in floods and in evaporation and evapotranspiration have not been  
8 detected globally. Some local trends in reduced groundwater and lake levels have been reported,  
9 but these are likely to be due to human activities rather than climate change. Climate change signals  
10 related to increasing runoff and streamflow have been observed over the last century in many  
11 regions, particularly in basins fed by glaciers, permafrost, and snowmelt. Evidence includes  
12 increases in average runoff of Arctic rivers in Eurasia, which has been at least partly correlated with  
13 climate warming, and earlier spring snowmelt and increase in winter base flow in North America  
14 and Eurasia due to enhanced seasonal snow melt associated with climate warming. There are also  
15 indications of intensified droughts in drier regions, particularly the Sahel region in Africa.  
16 Freshwater lakes and rivers are experiencing increased water temperature environments and  
17 changes in water chemistry. Surface and deep lake-waters are warming, with advances in and  
18 lengthening of periods of thermal stability in some cases associated with physical and chemical  
19 changes such as increases in salinity and suspended solids, and decrease in nutrient content. Lake  
20 formation and subsequent disappearance in permafrost have been reported in the Arctic.

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23 **1.3.3 Coastal processes and zones**

24

25 Many coastal regions are already experiencing the effects of relative (local) sea level rise, from a  
26 combination of climate-induced sea level rise, land subsidence, anthropogenic, and other local  
27 factors (Table 1.4). A major challenge, however, is to separate the different meteorological,  
28 oceanographic, geophysical, and anthropogenic processes affecting the shoreline in order to identify  
29 and isolate the contribution of global warming. These processes operate independently and can also  
30 interact with each other in complex feedback loops that cover a range of spatial and temporal  
31 scales. Therefore, an unambiguous attribution of current sea level rise as a primary driver of  
32 shoreline change is difficult at present.

33

34 Global sea level has been rising at a rate of ~1.7-1.8 mm/yr over the last century, with a possible  
35 acceleration during the last decade (Church *et al.* 2004; Holgate and Woodworth 2004; Church and  
36 White 2006). The effects of global sea level rise vary spatially because of local vertical land

1 motions (e.g., glacial isostatic adjustments, neotectonics, and/or subsurface fluid withdrawal), long-  
 2 shore currents, and cyclonicity (Church *et al.*, 2004). The worldwide increase in extreme high-water  
 3 levels since 1975 is closely linked to mean sea level rise and to indices of regional inter-annual to  
 4 inter-decadal climate variability such as the El Nino Southern Oscillation (ENSO), North Atlantic  
 5 Oscillation (NAO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO), Antarctic  
 6 Oscillation (AAO), and Indian Ocean Dipole (IND) (Woodworth and Blackman 2004). For  
 7 example, anomalously high sea surface temperatures and sea level in the Pacific Ocean were closely  
 8 correlated during the major 1997-1998 El Nino event (Nerem and Mitchum 2001).  
 9

10 **Table 1.4: Changes in coastal processes.**

Location	Period	Type of Change	Observed changes	Authors
Global	1950-2000;	Sea level rise	1.8 +/-0.3 mm/yr (tide gauges)	Church <i>et al.</i> , 2004
	1993-2000		2.6-2.7 +/-0.7 mm/yr (TOPEX/Poseidon)	
Global	1948-2002;	Sea level rise	1.7 +/-0.2 mm/yr (tide gauges)	Holgate and Woodworth, 2004
	1993-2000		2.8 mm/yr (TOPEX/Poseidon)	
East Coast USA, Long Island, NY to South Carolina	mid-1800s to 2000	Shoreline erosion	75% of the shoreline, uninfluenced by inlets and structures, is eroding	Zhang <i>et al.</i> , 2004
Louisiana, USA	1855-2002;	Shoreline erosion	0.61m/yr;	Penland <i>et al.</i> , 2005
	1988-2002		0.94 m/yr	
Fiji	1960s-1990s	Shoreline erosion	Beach erosion prevalent, due to sea level rise and mangrove clearance	Mimura and Nunn, 1998
Tropics--Southeast Asia, Indian Ocean, Australia, Barbados	c. 1950s-2000	Shoreline erosion	Beach erosion due to coral bleaching, mangrove clearance, sand mining, structures	Wong, 2003
Manitounuk Strait, Quebec, Canada	1950-1995	Shoreline change	19% of the studied shoreline is retreating, in spite of land uplift, due to thawing of permafrost	Beaulieu and Allard, 2003
Chesapeake Bay, USA	1938-1989	Wetland losses	~1700 ha degraded marshes in study area became open water; non-degraded marshes decreased by 1200 ha	Kearney <i>et al.</i> , 2002
Long Island, NY; Connecticut, USA	1920s-1999	Wetlands losses	Decreases in salt marsh area due to regional sea level rise and human impacts	Hartig <i>et al.</i> , 2002; Hartig and Gornitz, 2004
Normandy, France	1880-2000	Wetlands gains	Salt marshes keep up with sea level rise with sufficient sediment supply	Haslett <i>et al.</i> , 2003
Rhode Island, USA	1995-1999; late 20th century	Wetlands changes	Landward migration of cordgrass ( <i>Spartina alterniflora</i> ) due to sea level rise and excess nitrogen	Donnelly and Bertness, 2001; Bertness <i>et al.</i> , 2002
Southeast Florida, USA	1940-1994	Coastal vegetation changes	Grassy marshes replaced by mangrove due to sea level rise and changing water tables	Ross <i>et al.</i> , 2000

Western Florida, USA	1992-1998	Coastal vegetation changes	Loss of Southern red cedar ( <i>Juniperus virginiana</i> ) due to storms, droughts and sea level rise	Williams <i>et al.</i> , 2003
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### 1.3.3.1 Changes in coastal geomorphology

Beach erosion already affects an estimated 70% of the world's sandy beaches (Bird 1985; Bird 1993). Long-term beach erosion has been linked to historic rates of sea level rise on shorelines far from inlets and structures, (Zhang *et al.* 2004). However, in addition to sea level change, coastal erosion is driven by other geophysical factors such as wave energy, sediment supply, or local land subsidence (Stive 2004). In Estonia, the most active periods of shoreline displacement are associated with extreme climate events such as severe storms and high surge levels, which have been increasing in recent decades (Orviku *et al.* 2003). Reduction in sea ice cover, due to milder winters, has further exacerbated coastal damage there. Coastlines that are rising because of ongoing glacial rebound and that would otherwise be accreting have significant sections that are eroding, as for example along Hudson Bay, Canada (Beaulieu and Allard 2003). Degradation and melting of permafrost due to climate warming are contributing to rapid retreat of Arctic coastlines in many regions, such as the Beaufort and Laptev Seas coasts.

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Historic sea level rise is likely contributing to coastal erosion in many places (Leatherman *et al.* 2000; Zhang *et al.* 2004). Along the East Coast of the United States, 75% of the shoreline removed from the influence of spits, tidal inlets, and engineering structures are nonetheless eroding (Zhang *et al.* 2004). The high average annual erosion rate in the beach communities of Delaware's Atlantic coast (0.6-1.2 m/yr) is threatening the sustainability of the area as a major summer recreation attraction (Daniel 2001). The average rate of shoreline erosion in Louisiana was 0.61m/yr between 1855 and 2002; since 1988, rate of shoreline erosion have accelerated to 0.94 m/yr (Penland *et al.* 2005) and additional erosional losses were sustained after Hurricane Katrina, in August, 2005. Beach erosion has also increased in parts of Fiji (Mimura and Nunn 1998), the San Juan delta on the Pacific coast of South America (Restrepo *et al.* 2002), Trinidad in the Southern Caribbean (Singh and Fouladi 2003), and the tropics (Wong 2003).

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However, much of the observed beach erosion in Fiji and many other parts of the tropics is associated with development of the shoreline, clearing of mangroves, and mining of beach sand and coral. Another important contributor to coastal erosion is sediment starvation brought on by the construction of dams on major rivers (Chen *et al.* 2005; Syvitski *et al.* 2005; Ericson *et al.* 2006). Curtaillment of sediments reaching the shore has exacerbated coastal erosion in Louisiana (Georgiou *et al.* 2005; Penland *et al.* 2005). Most beaches in Alexandria, Egypt are eroding caused by sediment deficiency due to construction of dams and barrages across the Nile, combined with the natural reduction of Nile floods due to climatic changes over east Africa (Frihy *et al.* 1996). Pumping of groundwater and subsurface hydrocarbons enhances land subsidence, thereby also contributing to coastal erosion (Syvitski *et al.* 2005).

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### 1.3.3.2 Changes in coastal wetlands

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In the United States, losses in coastal wetlands have been observed in Louisiana (Boesch *et al.* 1994), the mid-Atlantic region (Kearney *et al.* 2002), and in parts of Connecticut and New York (Hartig and Gornitz 2004), in spite of recent protective environmental regulations (Kennish 2001). Many of these marshes have had a long history of anthropogenic modification, including dredging and filling, bulkheading, and channelization, which in turn could have contributed to sediment

1 starvation, eutrophication, and ultimately marsh submergence. In New England, low marsh  
2 cordgrass (*Spartina alterniflora*) has been migrating landward, partly in response to sea level rise,  
3 but also to increased nitrogen levels in estuaries (Donnelly and Bertness 2001; Bertness *et al.* 2002).  
4 A landward replacement of grassy freshwater marshes by more salt-tolerant mangroves in the  
5 south-eastern Florida Everglades since the 1940s has been attributed to the combined effects of sea  
6 level rise and water management practices that have resulted in lowered water tables (Ross *et al.*  
7 2000). On the other hand, some salt marsh losses stem from causes unrelated to sea level rise, such  
8 as predation by organisms or local weather events (e.g., in England (Hughes and Paramor 2004) and  
9 south-eastern U.S. (Silliman *et al.* 2005). Elsewhere, there is evidence that not all coastal wetlands  
10 are retreating, for example in northern France (Haslett *et al.* 2003).

11  
12 Tropical mangroves play an important role in trapping sediments, also in reducing the erosive potential  
13 of waves and currents (Furukawa *et al.* 1997; Mazda *et al.* 1997; Wolanski *et al.* 2002). Although  
14 natural accretion rates of mangroves generally compensate for current rates of sea level rise, of greater  
15 concern at present are the impacts of clearance for agriculture, aquaculture (particularly shrimp  
16 culture), forestry, and urbanization. At least 35 per cent of the world's mangrove forests were removed  
17 in the last two decades but possible sea-level rise effects were not considered (Valiela *et al.* 2001). In  
18 south-eastern Australia, mangrove encroachment inland into salt marsh environments is probably  
19 related to anthropogenic causes other than sea-level rise (Saintilan and Williams 1999).

20  
21 Climatic perturbations can also affect near shore vegetation. Coastal forest losses in western  
22 Florida have occurred as a consequence of storm damage and drought; however, the inability of the  
23 trees to regenerate may represent the effects of increasing salinity and greater frequency of tidal  
24 flooding due to sea level rise (Williams *et al.* 1999; Williams *et al.* 2003). Severe storms,  
25 especially hurricanes, have caused extensive wetlands losses. For example, Hurricane Katrina  
26 washed away an estimated 260 km<sup>2</sup> of coastal wetlands in Louisiana, in August, 2005. The area  
27 destroyed was more than 4 times the average annual rate of the 1990s, according to preliminary  
28 U.S. Geological Survey studies (Marris 2005).

### 29 30 1.3.3.3 *Changes in storm surges, flood heights and areas, and waves*

31  
32 The vulnerability of the coastal zone to storm surges and waves depends on soil subsidence,  
33 changes in storminess, and sea level rise. These three factors often interact and the effects of their  
34 superposition vary regionally (Table 1.5). Along the U.S. East Coast, although there has been no  
35 significant long-term change in storm climatology, storm surge impacts on the shore have increased  
36 due to the regional sea level rise (Zhang *et al.* 2000). The U.S. Gulf Coast is particularly vulnerable  
37 to hurricane surges, due to the low elevation and relative sea level rise (up to 1cm/yr along parts of  
38 the Louisiana coast) (Penland *et al.* 2005). Hurricane Katrina, in August, 2005, generated surges  
39 over 4 meters, with catastrophic consequences (NOAA. 2005). In Venice, Italy, the frequency of  
40 flooding surges in Venice has averaged close to 2 per year since the mid-1960s, as compared to  
41 only 0.19 surges per year between 1830-1930, with land subsidence (exacerbated by groundwater  
42 pumping between 1930-1970 (Carminati *et al.* 2005) and expanded sea-lagoon interactions (due to  
43 channel dredging) playing a greater role than global sea level rise (Camuffo and Sturaro 2004).  
44 Surges show a slight decrease in Brittany, France in recent decades, largely due to changes in wind  
45 patterns (Pirazzoli *et al.* 2004). Apparent global increases in extreme high water levels since 1975  
46 are also related to mean sea level rise and to large-scale interdecadal climate variability  
47 (Woodworth and Blackman 2004).

48  
49 In the northeast Atlantic Ocean, wave heights increased between 1970 to 1995 (Woolf *et al.* 2002), but  
50 appear to have decreased in some areas of the Mediterranean from 1958-2001 (Lionello 2005; Lionello  
51 and Sanna 2005). Significant open-water wave heights associated with powerful tropical cyclones in

1 the vicinity of Rarotonga, Cook Islands, have increased in recent years, as has the frequency of such  
 2 events. In the Indian Ocean, the rate of increase in extreme high water levels in Hulhule, the Maldives,  
 3 is about 4 times that of mean relative sea level rise (Govt. Maldives, 2006), possibly related to upward  
 4 trends in local air/sea surface temperatures and zonal winds (Woodworth, 2005). On the other hand,  
 5 no significant 20<sup>th</sup>-century trends in monsoon-related indices were observed.  
 6

7 **Table 1.5: Changes in storm surges, flood height and areas, and waves.**

Type of change	Period	Location	Authors
More frequent and higher floods due to subsidence, hydrodynamic changes, and relative sea level rise	1830-2000	Venice, Italy	Camuffo and Sturaro, 2004
Decreasing surges due to shifts in wind directions	1890s-1910s and 1950s-1997	Brittany, France	Pirazzoli <i>et al.</i> , 2004
Increasing extreme high water levels due to climate variability and sea level rise	1975-present	Global	Woodworth and Blackman, 2004
Decrease in mean winter significant wave height	1958-2001	Mediterranean Sea	Lionello and Sanna, 2005

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#### 10 1.3.3.4 Evidence of adaptation and vulnerability

11  
 12 In rural Fiji, islanders have responded to coastal erosion and sea encroachment over the last 40  
 13 years, in some cases, by constructing crude seawalls of stones and fences of sticks and debris,  
 14 which are fairly ineffective protection against major storms (Mimura and Nunn 1998). Retreat from  
 15 the shore or island abandonment is an extreme case of adaptation to rising seas. For example, the  
 16 inhabitants of Tuvalu have considered relocation elsewhere, in anticipation of future sea level rise  
 17 (ref. needed). In a few isolated cases, previously inhabited low-lying islands have been abandoned;  
 18 for example, several Chesapeake Bay islands in the U.S. were abandoned in the early 20th century  
 19 (Gibbons and Nicholls 2006). In the United States, approximately \$1.3 billion (adjusted to 1996  
 20 dollars) have been spent between the 1960s and 1990s on beach nourishment, in response to coastal  
 21 erosion. Japan spends over US\$240 million annually on port restoration due to high waves, storm  
 22 surges, and other natural disasters.  
 23

#### 24 1.3.3.5 Summary

25  
 26 In many coastal regions, local sea level rise exceeds the global trend of 1.7 to 1.8 mm/yr, although  
 27 much higher rates exist in subsiding regions. Sea-level rise, enhanced wave heights, and increased  
 28 intensity of storms are affecting some coastal regions distant from human modification, e.g., polar  
 29 areas and barrier beaches, mainly through coastal erosion. Coastal erosion and wetlands losses are  
 30 widespread problems today, under current rates of sea level rise. These are largely caused by  
 31 anthropogenic modification of the shoreline. A few isolated cases of historic island abandonment  
 32 due to rising seas have been documented, and residents of presently inhabited islands such as  
 33 Tuvalu, are finding it increasingly difficult to maintain their lifestyles, due to climate-induced  
 34 environmental changes.  
 35  
 36

#### 37 1.3.4 Marine and freshwater biological systems

38  
 39 The marine pelagic realm occupies 70% of the planetary surface (Legendre and Rivkin 2002). The

1 pelagic ecosystem plays a fundamental role in modulating the global environment via its regulatory  
2 effects on the Earth's climate and its role in biogeochemical cycling. Perhaps equally important to  
3 global climate change, in terms of modifying the biology of the oceans, is the impact of  
4 anthropogenic CO<sub>2</sub> on the pH of the oceans that will affect the process of calcification for some  
5 marine organisms (Feely *et al.* 2004). Other driving forces of change that are operative in marine  
6 and freshwater biological systems are overfishing and pollution from terrestrial runoff (from  
7 deforestation, agriculture and urban development) and human introductions of non-native species.

8  
9 Any observational change in marine and freshwater environments associated with climate change  
10 should be considered against the background of natural variation on a variety of spatial and  
11 temporal scales. Recently long-term decadal observational studies have focused on known natural  
12 modes of climatic oscillations at similar temporal scales such as the El Nino-Southern Oscillation  
13 (ENSO) in the Pacific and the North Atlantic Oscillation (NAO) in relation to ecosystem changes  
14 (Stenseth *et al.* 2002). Many of the biological responses observed have been associated with rising  
15 temperatures. However, discerning the effects of climate change embedded in natural modes of  
16 variability such as the NAO is difficult and direct evidence of biological impacts of anthropogenic  
17 climate change must be treated with caution.

18  
19 Within the marine biological systems, coral reefs are iconic, highly diverse ecosystems of enormous  
20 economic, cultural and aesthetic value. Located within a broad latitudinal band from 30°N to 30°S,  
21 the geographic spread of reefs encompasses a wide range of physical and chemical conditions (e.g. in  
22 temperature, alkalinity, turbidity and productivity). Habitats associated with coral reefs include  
23 mangrove forests and seagrass beds. Besides pollution, scuba diving by tourists also places stress on  
24 coral reefs.

25  
26 Many changes in marine commercial fish stocks have been observed over the last few decades in  
27 the Atlantic and Pacific Oceans but it is difficult to separate, in terms of changes in population  
28 densities and recruitment, regional climate effects from direct anthropogenic influences like fishing.  
29 Geographical range extensions or changes in the geographical distribution of fish populations,  
30 however, can be more confidently linked to hydro-climatic variation and regional climate warming.

31  
32 Freshwater biological systems of lakes and rivers are highly susceptible to changes in temperature.  
33 This has been clearly demonstrated by paleolimnologic approaches examining changes on  
34 millennial time scales. The same paleolimnological techniques, along with the increasing amount  
35 and length of empirical data records, indicate that these freshwater systems are responding to recent  
36 climate warming (Schindler *et al.* submitted). The type and magnitude of the response to climate  
37 change depends upon many factors, including size, water depth/flow, latitude, and altitude.

#### 38 39 1.3.4.1 Changes in coral reefs

40  
41 Overfishing and pollution have reduced coral reef resilience, i.e., the regenerative capacity of corals  
42 is impaired following disturbances such as hurricanes or bleaching events caused by warm sea  
43 surface temperature events (Bellwood *et al.* 2004). The ability of reefs to cope with climate change  
44 is pre-conditioned by the extent to which they are already overfished and polluted (Hughes *et al.*  
45 2003; Pandolfi *et al.* 2003). (See Chapter 11, Box 11.1.)

46  
47 The most visible manifestation of climate change occurs when stressed corals become pale and  
48 bleached due to the loss of their endosymbiotic micro-algae (zooxanthellae); this occurs within 2-4  
49 weeks. Regional-scale bleaching events have become increasingly prevalent since the 1980s.  
50 Recurrent bleaching was first documented in the eastern Pacific, the Caribbean and Polynesia. In  
51 1998, the largest bleaching event to date killed an estimated 16% of the world's corals, primarily in

1 the western Pacific and the Indian Ocean, linked to the El Niño event of that year (Wilkinson 2004).  
2 Bleaching is highly selective, affecting species and strains (of both corals and zooxanthellae) to  
3 different extents (Loya *et al.* 2001; Coles and Brown 2003; Little *et al.* 2004). The mechanisms  
4 underlying this variation are poorly understood. Bleached corals have markedly higher rates of  
5 mortality. However, some corals regain zooxanthellae and can recover from bleaching, although  
6 they may suffer temporary reductions in growth and reproductive capacity (Baker *et al.* 2004; Little  
7 *et al.* 2004).

8  
9 Rising sea surface temperatures have been linked with coral bleaching. Bleaching usually occurs  
10 when temperatures exceed a ‘threshold’ of ~2°C above mean summer maximum levels for several  
11 weeks. Maximum temperatures range by more than 10°C within the geographic boundaries of most  
12 species (e.g. along latitudinal gradients). Cooler locations have lower bleaching thresholds, implying  
13 that there is strong local acclimation to thermal conditions, and ongoing evolution of temperature  
14 tolerance (Hughes *et al.* 2003). How quickly further evolutionary responses can occur is unknown.

15  
16 The incidence of disease in corals, gorgonians, sea urchins and other reef organisms has increased,  
17 especially on reefs that are already degraded (Harvell *et al.* 2002). The trend in species composition  
18 in favour of weedy species that can colonize and grow quickly suggests that reefs are being exposed  
19 to more frequent and intense tropical storms (Nystrom *et al.* 2000; Bellwood *et al.* 2004).

#### 20 21 1.3.4.2 *Changes in marine ecosystems*

22  
23 There is an accumulating body of evidence to suggest that many marine ecosystems, including  
24 managed fisheries, both physically and biologically, are responding to changes in regional climate  
25 caused predominately by warming of air and sea surface temperatures (SSTs) and to a lesser extent  
26 by modification of precipitation regimes and wind patterns (Table 1.6). The biological  
27 manifestations of rising SSTs have included biogeographical, phenological, physiological and  
28 species abundance changes. Evidence collected and modelled to date indicates that rising CO<sub>2</sub> has  
29 led to chemical changes in the ocean which has led to the oceans becoming more acidic (Society  
30 2005). Satellite-in situ blended ocean chlorophyll records indicate that global ocean annual primary  
31 production has declined more than 6% since the early 1980s (Gregg *et al.* 2003) (Fig. 1.1b).

32  
33 In the Pacific, researchers have found similar changes to the intertidal communities where the  
34 composition has shifted significantly in response to warmer temperatures (Sagarin *et al.* 1999).  
35 Similar shifts were also noted in the kelp forest fish communities off the southern Californian coast  
36 and in the offshore zooplankton communities (Roemmich and McGowan 1995; Holbrook *et al.*  
37 1997; Lavaniegos and Ohman 2003). These changes are associated with oceanic warming and the  
38 resultant geographical movements of species with warmer water affinities. Like the North Atlantic,  
39 many long-term biological investigations in the Pacific have established links between changes in  
40 the biology and regional climate oscillations such as the ENSO and the Pacific Decadal Oscillation  
41 (PDA) (Stenseth *et al.* 2002). In the case of the Pacific these biological changes are most strongly  
42 associated with El Niño events which can cause rapid and sometimes dramatic responses to the  
43 short-term SST changes accompanying El Niño events (Hughes 2000).

44  
45 The progressive warming in the Southern Ocean has been associated with krill decline (Atkinson *et al.*  
46 2004), decline in the population sizes of many seabirds and seals monitored on several breeding  
47 sites (Barbraud and Weimerskirch 2001; Weimerskirch *et al.* 2003), and an increase in the  
48 incidence of marine diseases (Harvell *et al.* 1999).

49  
50 In the North Atlantic, both changes in phytoplankton and zooplankton species and communities  
51 have been associated with Northern Hemisphere Temperate (NHT) trends and variations in the

1 NAO index. These have included changes in species distributions and abundance, the occurrence of  
2 sub-tropical species in temperate waters, changes in overall phytoplankton biomass and seasonal  
3 length, changes in the North Sea ecosystem functioning and productivity, shifts from cold-adapted  
4 to warm-adapted communities, phenological changes and changes in species interactions  
5 (Fromentin and Planque 1996; Reid *et al.* 1998; Edwards *et al.* 2001; Reid and Edwards 2001;  
6 Beaugrand *et al.* 2002; Edwards *et al.* 2002; Beaugrand *et al.* 2003; Beaugrand and Reid 2003;  
7 Edwards and Richardson 2004; Richardson and Schoeman 2004). Over the last decade, numerous  
8 other investigations have established links between the NAO and the biology of the North Atlantic  
9 including the benthos, fish, seabirds and whales (Drinkwater *et al.* 2003). In the Benguela  
10 upwelling system in the South Atlantic, long-term trends in the abundance and community structure  
11 of coastal zooplankton have been related to large-scale climatic influences (Verheye *et al.* 1998).

12  
13 Recent macroscale research has shown that the increase in regional sea temperatures has triggered a  
14 major re-organisation in calanoid copepod species composition and biodiversity over the whole  
15 North Atlantic basin (Beaugrand *et al.* 2002). During the last 40 years there has been a northerly  
16 movement of warmer water plankton by 10° latitude in the north-east Atlantic and a similar retreat  
17 of colder water plankton to the north. This geographical movement is much more pronounced than  
18 any documented terrestrial study, presumably due to advective processes. In terms of the marine  
19 phenological response to climate warming, many plankton taxa have been found to be moving  
20 forward in their seasonal cycles (Edwards and Richardson 2004). In some cases a shift in seasonal  
21 cycles of over six weeks was detected, but more importantly the response to climate warming  
22 varied between different functional groups and trophic levels, leading to mismatch in timing  
23 between different trophic levels (Edwards and Richardson 2004).

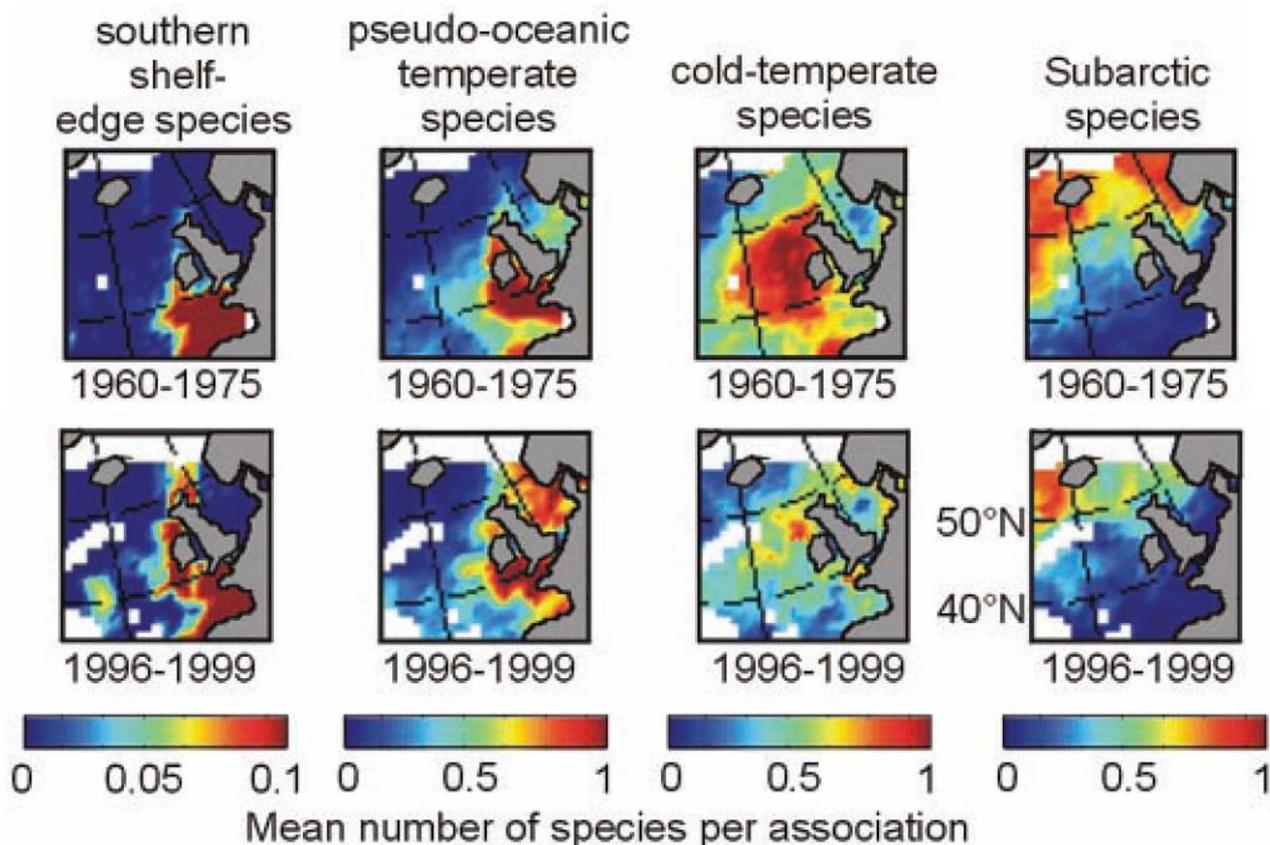
#### 24 25 1.3.4.3 Changes in fisheries

26  
27 Similar to the observed changes in marine ecological systems (section 1.3.4.5) many long-term  
28 changes in fish populations have been associated with known natural modes of climatic oscillations  
29 such as the ENSO and NAO (Stenseth *et al.* 2002; Drinkwater *et al.* 2003).

30  
31 Northerly geographical range extensions or changes in the geographical distribution of fish  
32 populations have been recently documented for European Continental shelf seas and along the  
33 European Continental shelf edge (Fig. 1.3) (Brander *et al.* 2003; Beare *et al.* 2004; Genner *et al.*  
34 2004; Perry *et al.* 2005). These geographical movements have been related with regional climate  
35 warming and are predominantly associated with the northerly geographical movement of fish species  
36 with more southern biogeographical affinities. These include the movement of sardines and  
37 anchovies northward in the North Sea and red mullet and bass extending their ranges northward to  
38 western Norway (Brander *et al.* 2003; Beare *et al.* 2004). New records were also observed over the  
39 last decade for a number of Mediterranean and north-west African species on the south coast of  
40 Portugal (Brander *et al.* 2003). The cooling and the freshening of the north-west Atlantic (such as in  
41 the sub-polar gyre, Labrador sea and Labrador current) over the last decade has had an opposite  
42 effect, with some groundfish species moving further south in their geographical distribution (Rose  
43 and O'Driscoll 2002).

44  
45 Regional climate warming in the North Sea has affected cod recruitment via changes at the base of  
46 the food web (Beaugrand *et al.* 2003). Cod, like many other fish species, are highly dependent on  
47 the availability of planktonic food during their pelagic larval stages. Key changes in the planktonic  
48 assemblage, significantly correlated with the warming of the North Sea over the last few decades,  
49 has resulted in a poor food environment for cod larvae and hence eventual decline in overall  
50 recruitment success. This research is an example of how the dual pressures of over-fishing and  
51 regional climate warming have conspired together to negatively affect a commercially important

1 fishery. Recent work on pelagic phenology has shown that plankton communities, including fish  
 2 larvae, are very sensitive to regional climate warming with the response to warming varying  
 3 between trophic levels and functional groups (Edwards and Richardson 2004). These changes,  
 4 again seen in the North Sea, have the potential to be of detriment to commercial fish stocks via  
 5 trophic mismatch. The ability and speed with which fish and planktonic communities adapt to  
 6 regional climate warming is not yet known.



32 *Fig. 1.3: Long-term changes in the mean number of marine species per association in the North*  
 33 *Atlantic from 1960 to 1999 (Beaugrand et al. 2002).*

36 **Table 1.6: Changes in marine ecosystems and managed fisheries.**

Key changes	Climate link	Location	References
Pelagic productivity/ Zooplankton abundance/ plankton assemblages	Biological responses to regional changes in temperature, stratification, upwelling, and other hydro-climatic changes.	North Atlantic  North Pacific  South Atlantic Southern Ocean	Fromentin & Planque, 1996; Reid et al, 1998; Edwards <i>et al.</i> 2001, 2002; Johns <i>et al.</i> 2003; Beaugrand & Reid, 2003; Beaugrand <i>et al.</i> 2003; Richardson & Schoeman, 2004  Roemmich and McGowan, 1995; McGowan, <i>et al.</i> 1998; Walther <i>et al.</i> 2002; Lavaniegos & Ohman, 2003; Verheye <i>et al.</i> 1998; Walther <i>et al.</i> 2002; Atkinson <i>et al.</i> 2004
Pelagic phenology	Earlier seasonal appearance due to increased temperature and trophic mismatch	North Sea	Edwards & Richardson, 2004; Greve, 2004

Pelagic biogeography	Northerly movement of plankton communities due to general warming	North Atlantic	Beaugrand <i>et al.</i> 2002
Rocky shore/intertidal communities	Community changes due to regional temperature changes	British Isles North Pacific	Hawkins <i>et al.</i> 2003 Sagarin <i>et al.</i> 1999
Kelp forests/macroalgae	Effect on communities and spread of warmer-water species due to increased temperatures	North Pacific Mediterranean	Holbrook <i>et al.</i> 1997; McGowen, <i>et al.</i> 1998; Walther <i>et al.</i> 2002
Marine pathogens and invasive species	Geographical range shifts due to increased temperatures	North Atlantic	Harvell <i>et al.</i> 1999; Walther <i>et al.</i> 2002; McCallum <i>et al.</i> 2003;
Fish populations and recruitment success	Changes in populations, recruitment success, trophic interactions, and migratory patterns related to regional environmental change	British Isles North Pacific North Atlantic  Barents Sea Mediterranean	Attrill & Power, 2002; Genner <i>et al.</i> 2004 McGowen, <i>et al.</i> 1998; Chavez <i>et al.</i> 2003 Walther <i>et al.</i> 2002; Drinkwater <i>et al.</i> 2003; Beaugrand & Reid, 2003; Beaugrand <i>et al.</i> 2003; Brander <i>et al.</i> 2003 Stenseth <i>et al.</i> 2002; Walther <i>et al.</i> 2002 Walther <i>et al.</i> 2002
Fish biogeography	Geographical range shifts related to temperature	NE Atlantic  NW Atlantic	Beare <i>et al.</i> 2004; Brander <i>et al.</i> 2003; Genner <i>et al.</i> 2004; Perry <i>et al.</i> 2005 Rose & O'Driscall, 2002
Seabirds and marine mammals	Population changes, migratory patterns, trophic interactions and phenology related to regional environmental change	North Atlantic North Pacific  Southern Ocean	Drinkwater <i>et al.</i> 2003; Walther <i>et al.</i> 2002 McGowen, <i>et al.</i> 1998; Hughes 2000; Walther <i>et al.</i> 2002 Barbraud & Weimerskirch, 2001; Weimerskirch <i>et al.</i> 2003
Marine biodiversity	Regional response to general warming	North Atlantic	Beaugrand <i>et al.</i> 2002

1

2

3 *1.3.4.4 Changes in freshwater ecosystems*

4

5 Observations indicate that lakes and rivers around the world are warming, with effects on thermal  
6 structure and lake chemistry that in turn affect abundance and productivity, community  
7 composition, phenology, distribution and migration (see also 1.3.2) (Table 1.3c and Table 1.7).

8

9 *Abundance/productivity.* There have been changes in lake productivity and plankton abundance. In  
10 high latitude or high altitude lakes where reduced ice cover has led to a longer growing season and  
11 warmer temperatures, many lakes are showing increased algal abundance and productivity over the  
12 past century (Schindler *et al.* 1990; Hambright *et al.* 1994; Gajewski *et al.* 1997; Wolfe and Perren  
13 2001; Battarbee *et al.* 2002; Korhola *et al.* 2002; Karst-Riddoch *et al.* 2005). There have been  
14 similar increases in the abundance of zooplankton, correlated to warmer water temperatures and  
15 longer growing seasons (Adrian and Deneke 1996; Weyhenmeyer *et al.* 1999; Straile and Adrian  
16 2000; Battarbee *et al.* 2002; Gerten and Adrian 2002; Carvalho and Kirika 2003; Winder and  
17 Schindler 2004; Hampton 2005; Schindler *et al.* 2005). For upper trophic levels, rapid increases in  
18 water temperature after ice breakup have enhanced fish recruitment in oligotrophic lakes (Nyberg *et al.*  
19 2001). In contrast to these lakes, some lakes, particularly deep tropical lakes, are experiencing  
20 reduced algal abundance and declines in productivity because stronger stratification reduces

1 upwelling of nutrient-rich deep water (Adrian *et al.* 1995; Verburg *et al.* 2003; O'Reilly 2006).  
2 Primary productivity in Lake Tanganyika may have decreased by up to 20% over the past 200 years  
3 (O'Reilly *et al.* 2003), and for the East African Rift Valley lakes, recent declines in fish abundance  
4 have been linked with these climatic impacts on lake ecosystems (O'Reilly 2006).

5  
6 *Community composition.* Increases in the length of the ice-free growing season, greater  
7 stratification, and changes in relative nutrient availability have generated shifts in community  
8 composition. Paleolimnological records showed widespread changes in phytoplankton species  
9 composition since the mid to late-1800s due to climate shifts, with increases in chrysophytes and  
10 planktonic diatom species and decreases in benthic species (Gajewski *et al.* 1997; Wolfe and Perren  
11 2001; Battarbee *et al.* 2002; Sorvari *et al.* 2002; Laing and Smol 2003; Michelutti *et al.* 2003;  
12 Perren *et al.* 2003; Ruhland *et al.* 2003; Karst-Riddoch *et al.* 2005; Smol *et al.* 2005). These  
13 sedimentary records also indicated changes in zooplankton communities (Douglas *et al.* 1994;  
14 Battarbee *et al.* 2002; Korhola *et al.* 2002; Brooks and Birks 2004; Smol *et al.* 2005). In relatively  
15 productive lakes, there was a shift towards more diverse periphytic diatom communities due to  
16 increased macrophyte growth (Karst-Riddoch *et al.* 2005). In lakes where nutrients are becoming  
17 limited due to increased stratification, phytoplankton composition shifted to relatively fewer  
18 diatoms, potentially reducing food quality for upper trophic levels (Adrian and Deneke 1996;  
19 Verburg *et al.* 2003; O'Reilly 2006). Climate warming has also produced a northward shift in  
20 Odonata ranges in Britain (Hickling *et al.* 2005).

21  
22 *Phenology.* With earlier ice breakup and warmer water temperatures, some species have responded  
23 to the earlier commencement of the growing season, often advancing development of spring algal  
24 blooms as well as clear water phases. The spring algal bloom now occurs about 4 weeks earlier in  
25 several large lakes (Weyhenmeyer *et al.* 1999; Gerten and Adrian 2000; Straile and Adrian 2000;  
26 Winder and Schindler 2004). In many cases where the spring phytoplankton bloom has advanced,  
27 zooplankton have not responded similarly, and their populations are declining because their  
28 emergence no longer corresponds with high algal abundance (Gerten and Adrian 2000; Winder and  
29 Schindler 2004). However, zooplankton phenology has also been affected by climate (Gerten and  
30 Adrian 2002; Winder and Schindler 2004). Phenological shifts have also been demonstrated for  
31 some wild and farmed fish species (Ahas 1999; Elliott *et al.* 2000). Because not all organisms  
32 respond similarly, differences in the magnitude of phenological responses among species has  
33 affected food web interactions (Winder and Schindler 2004).

#### 34 35 1.3.4.5 *Changes in rivers*

36  
37 Water flow is an important constraint in rivers that can influence water chemistry, habitat, and  
38 population dynamics, in addition to also affecting water temperature (Schindler *et al.* submitted).  
39 Specific information on the effect of climate change on hydrology can be found in Section 1.3.2.  
40 Increasing river temperatures have been associated with increased biological demand and decreased  
41 dissolved oxygen (without changes in flow) (Ozaki *et al.* 2003). Riverine dissolved organic carbon  
42 concentrations have doubled in some cases because of increased carbon release in the catchment as  
43 temperature has risen (Worrall *et al.* 2003).

44  
45 *Abundance, distribution and migration.* Climate-related changes in rivers have affected species  
46 abundance, distribution, and migration patterns. While warmer water temperatures in many rivers  
47 have positively influenced the breeding success of fish (Fruget *et al.* 2001; Grenouillet *et al.* 2001;  
48 Daufresne *et al.* 2004), the stressful period associated with higher water temperatures for salmonids  
49 has lengthened as water temperatures have increased commensurate with air temperatures in some  
50 locations (Bartholow 2005). In the Rhone River, there have been significant changes in species  
51 composition, as southern, thermophilic fish and invertebrate species have progressively replaced

1 cold-water species (Doledec *et al.* 1996; Daufresne *et al.* 2004). Correlated with long-term  
 2 increases in water temperature related to climate change, the timing of fish migrations in large  
 3 rivers in North America has advanced by up to 6 weeks in some years (Quinn and Adams 1996;  
 4 Huntington *et al.* 2003; Cooke *et al.* 2004; Juanes *et al.* 2004). Increasing air temperatures have  
 5 been negatively correlated with smolt production (Lawson *et al.* 2004) and earlier migrations are  
 6 associated with greater en route and pre-spawning mortality (up to 90%) (Cooke *et al.* 2004).

#### 8 1.3.4.6 Summary

10 In marine and freshwater ecosystems, many observed changes in phenology and distribution have  
 11 been associated with rising water temperatures, as well as changes in salinity, oxygen levels, and  
 12 circulation. Climate change and variability, in combination with human impacts, have already  
 13 caused substantial damage to coral reefs. Globally, freshwater ecosystems are showing changes in  
 14 organism abundance and productivity, northward range expansions, and phenological shifts  
 15 (including earlier fish migrations) that are linked to rising temperatures. Many of these climate-  
 16 related impacts are now influencing how marine and freshwater ecosystems function.

18 **Table 1.7: Examples of changes in freshwater ecosystems due to climate warming.**

Environmental factor	Change	Time period of change	Location of lakes/rivers	# of lakes/rivers studied	Selected References
Productivity or biomass	Increases due to longer growing season	100 years	North America, Europe	26	(Schindler <i>et al.</i> 1990; Adrian and Deneke 1996; Gajewski <i>et al.</i> 1997; Weyhenmeyer <i>et al.</i> 1999; Straile and Adrian 2000; Wolfe and Perren 2001; Battarbee <i>et al.</i> 2002; Gerten and Adrian 2002; Korhola <i>et al.</i> 2002; Carvalho and Kirika 2003; Winder and Schindler 2004; Hampton 2005; Karst-Riddoch <i>et al.</i> 2005; Schindler <i>et al.</i> 2005)
	Decreases due to decreased nutrient availability	100 years	Europe, East Africa	5	(Adrian <i>et al.</i> 1995; O'Reilly <i>et al.</i> 2003; Verburg <i>et al.</i> 2003; O'Reilly 2006)
Algal community composition	Shift from benthic to planktonic species	150 to 100 years	North America, Europe	66	(Gajewski <i>et al.</i> 1997; Wolfe and Perren 2001; Battarbee <i>et al.</i> 2002; Sorvari <i>et al.</i> 2002; Laing and Smol 2003; Michelutti <i>et al.</i> 2003; Perren <i>et al.</i> 2003; Ruhland <i>et al.</i> 2003; Karst-Riddoch <i>et al.</i> 2005; Smol <i>et al.</i> 2005)
	Decreased diatom abundance	100 years	East Africa, Europe	3	(Adrian and Deneke 1996; Verburg <i>et al.</i> 2003; O'Reilly 2006)
Phenology	Spring algal bloom up to 4 weeks earlier, earlier clear water phase, etc.	45 years	North America, Europe	5	(Weyhenmeyer <i>et al.</i> 1999; Gerten and Adrian 2000; Straile and Adrian 2000; Gerten and Adrian.R. 2002; Winder and Schindler 2004; Winder and Schindler 2004)
Fish migration	6 days to 6 weeks earlier	50 to 20 years	North America	5	(Quinn and Adams 1996; Huntington <i>et al.</i> 2003; Cooke <i>et al.</i> 2004; Juanes <i>et al.</i> 2004; Lawson <i>et al.</i> 2004)

19

1

2 **1.3.5 Terrestrial biological systems**

3

4 Plants and animals can successfully reproduce, grow and survive only within specific ranges of  
5 climatic and environmental conditions (e.g., soil nutrients, roosting sites). If these conditions  
6 change beyond species' tolerances, then plants and animals respond by shifting in space, timing of  
7 life cycles, morphology, reproduction and productivity, which could influence species compositions  
8 in ecosystems. If none of these responses is possible, local populations of species are likely to  
9 become extinct. Since the TAR, the number of studies finding species within terrestrial ecosystems  
10 to have responded to changing climate (associated with varying levels of confidence) has risen  
11 substantially. Recent global reviews are by Hughes (Hughes 2000), Menzel and Estrella (Menzel *et al.*  
12 *2001*), Walther (Walther *et al.* 2002), Sparks and Menzel (Sparks and Menzel 2002), Parmesan  
13 (Parmesan and Yohe 2003) and Root (Root and Schneider 2002; Root *et al.* 2003); reviews on  
14 regional scales are by Parmesan and Galbraith for the US (Parmesan and Galbraith 2004) and the  
15 EEA for Europe (EEA 2004).

16

17 The likely influence of non-climate driving forces on biological responses increases with complexity  
18 of the processes studied, from phenology to morphology to ecosystems. Plants and animals may be  
19 affected by increased levels of UV-B radiation (Cummins 2003); plants are also affected by soluble-  
20 nitrogen deposition (Korner 2000). Species interactions and species-specific responses to various  
21 drivers – competition, pests and diseases, natural disturbances (e.g., wildfires), and soil properties  
22 (e.g., nutrient availability) also influence the changes seen in species. Other factors such as land use  
23 and land-use changes, habitat fragmentation (Hill *et al.* 1999) (Warren *et al.* 2001) or simply the  
24 absence of suitable areas for colonization, e.g., at higher elevations, also play an important role  
25 (Wilson *et al.* 2005), especially in species extinction (Williams *et al.* 2003). Animal distribution is  
26 dependent on the availability of suitable habitats for reproduction, raising of offspring, feeding, and  
27 wintering. Many animal populations have been under pressure from agricultural intensification and  
28 land-use change in the past 50 years and many species are in decline.

29

30 **1.3.5.1 Morphological and physiological changes**

31

32 *In-situ* observations provide evidence of morphological changes in vertebrates that appear linked to  
33 climatic change. Changes in morphological traits of birds apparently associated with temperature,  
34 probably via food availability, have been reported for the river warbler (Kanuscak *et al.* 2004).  
35 Reading and Clarke (Reading and Clarke 1999) report some changes in toad (*Bufo* spp.)  
36 reproduction related to temperature, precipitation, and population density. There have been reported  
37 instances of egg-size changes in birds related to temperature, but examples of both larger (Jarvinen  
38 1994; Jarvinen 1996) and smaller eggs as evolutionary reaction to decreasing of female body size in  
39 long-term period have been reported (Tryjanowski *et al.* 2004). Following Bergmann's rule,  
40 homeothermic ('warm-blooded') animals are expected to become smaller with rising average  
41 temperatures (Yom-Tov 2001). However, several studies on birds and mammals also revealed a  
42 trend towards larger body size in spite of globally and regionally increasing ambient temperatures  
43 (Nowaowski *et al.* 2002; Yom-Tov 2003; Kanuscak *et al.* 2004; Yom-Tov and Yom-Tov 2004),  
44 which may be explained by increased food supply and altered habitat structure.

45

46 In the insectivorous barn swallow, temperature affects not only egg mass, but also concentration of  
47 maternally derived substances that can affect egg hatchability and offspring antiparasite defence  
48 and viability (Saino *et al.* 2004). Northwards range extension by some Orthoptera and butterflies  
49 has been assisted by the evolution of increased colonization capacity (flight duration) and  
50 morphology (increased wing length and wing musculature, but decreased reproductive output (Hill  
51 *et al.* 1999; Thomas *et al.* 2001; Hughes *et al.* 2003; Simmons and Thomas 2004).

### 1.3.5.2 Changes in phenology

Phenology – the timing of seasonal activities of animals and plants – is perhaps the simplest process in which to track changes in the ecology of species in response to climate change. Recorded changes in spring and summer phenological events of plants and animals include leaf unfolding, flowering, fruit ripening of plants, arrival of migrant birds, chorusing of amphibians, and appearance/emergence of butterflies, while phenological changes in autumn include later leaf colouring, leaf fall, and migration of some birds. Numerous studies concurrently document both a progressively earlier start, and a later ending, thereby creating a lengthening of the growing season in most parts of the temperate and boreal zone of the northern hemisphere during the last 2-5 decades (see Table 1.8). A corresponding lengthening is observed for the frost-free growing season in North America and Europe (see 1.3.6.2).

Global meta-analyses have documented mean advances of spring events by 2.3 and 5.1 days/decade (the former includes species that have shown no change (Parmesan and Yohe 2003), while the latter includes only changing species (Root *et al.* 2003). Three other methods provide similar results (Penuelas and Filella 2001; Lucht *et al.* 2002): (1) analyses of remotely sensed vegetation indices (Myneni *et al.* 1997; Zhou *et al.* 2001), (2) analysis of the atmospheric CO<sub>2</sub> signal (Keeling *et al.* 1996) (both providing spatially and species-averaged information), and (3) analyses of phenological ground observations (reviewed by Menzel *et al.* 2001; Sparks and Menzel 2002; Walther *et al.* 2002; Menzel 2003; Walther 2004).

Although phenological network studies differ in regions, species, events observed, and applied methods, their data show a clear extension of the growing season by up to 2 weeks in the 2<sup>nd</sup> half of the 20<sup>th</sup> century in mid and high latitudes of the northern hemisphere. A lengthened growing season might account for observed increases in productivity (see 1.3.6). Analyses of single-station data indicate a much greater lengthening of the growing season of 32 days in Spain (1952-2000) (Penuelas *et al.* 2002), or a pronounced earlier birch leaf fall in Russia (1930-1998) (Kozlov and Berlina 2002).

**Table 1.8:** Changes in length of growing season, based on observations within networks.

Location	Period	Species/Indicator (LU leaf unfolding, LC leaf colouring, LF leaf fall)	Lengthening [Days/decade]	Author
Germany	1951 up to 2000	4 deciduous trees (LU to LC)	1.1 to 2.3 (all stations, records)	(Menzel <i>et al.</i> 2001) (Menzel <i>et al.</i> 2003)
Switzerland	1951-2000	9 spring phases, 6 autumn phases	2.7 (only sign. changes)	(Defila and Clot 2001)
Europe (Int. Phenological Gardens)	1959-1996	Various spring / autumn phases (LU to LC, LF)	3.5 (all stations)	(Menzel and Fabian 1999; Menzel 2000)
Japan	1953-2000	Gingko biloba (LU to LF)	2.6	(Matsumoto <i>et al.</i> 2003)
Northern Hemisphere	Jul 1981 – Dec 1999	Growing season by NDVI	1 (Eurasia), 0.7 (North America)	(Zhou <i>et al.</i> 2001)

Altered timing of spring events are reported for a broad multitude of species and locations (e.g., swallow arrival time in the Slovak Republic (Sparks and Braslavská 2001) or Aspen flowering in Canada (Beaubien and Freeland 2000) (see further examples in supplementary material). Network studies where results from all sites are reported, irrespective of their significance (Table 1.9), show that leaf unfolding and flowering have, on average, advanced by 1-3 days per decade in Europe, North America, and Japan over the last 30 to 50 years. There are also indications that the onset of fruit ripening has advanced in many cases (Jones and Davis 2000; Penuelas *et al.* 2002; Menzel *et al.* 2003).

1

2 **Table 1.9:** Changes in the timing of spring events, based on observations within networks.

Location	Period	Species / Indicator (F=flowering, LU leaf unfolding))	Observed changes (- advance, + delay) [Days/decade]	Author
Western USA	1957-1994	Lilac, honeysuckle (F)	-1.5 / -3.5	(Cayan 2001)
Northeast USA	1965-2001 1959-1993	Lilac (F, LU) Lilac (F)	-3.4 / -2.6 -1.7	(Wolfe <i>et al.</i> 2005) (Schwartz and Reiter 2000)
Washington, DC	1970-1999	100 plant species (F)	-0.8	(Abu-Asab <i>et al.</i> 2001)
Germany	1951-2000	10 spring phases (F, LU)	-1.6	(Menzel <i>et al.</i> 2003)
Switzerland	1951-1998	9 spring phases (F, LU)	-1.9	(Defila and Clot 2001)
Europe (Int. Phenological Gardens)	1959-1996	Different spring phases (F, LU)	-2.1	(Menzel and Fabian 1999) (Menzel 2000)
Europe (Int. Phenological Gardens)	1969-1998	Different spring phases index	-2.7	(Chmielewski and Rotzer 2001)
21 European Countries	1971-2000	F, LU of various plants	-2.5	(Menzel <i>et al.</i> 2006)
Japan	1953-2000	Ginkgo biloba (LU)	-0.9	(Matsumoto <i>et al.</i> 2003)
Northern Eurasia	1982-2004	NDVI	-1.5	(Delbart <i>et al.</i> 2006)
UK	Past 23 years	18 butterfly species appearance	- 2.8 to -3.2	(Roy and Sparks 2000)
Europe, North America	Past 30-60 years	Numerous bird species	Earlier spring migration by 1.3-4.4 days/decade	(Crick <i>et al.</i> 1997; Crick and Sparks 1999; Dunn and Winkler 1999; Inouye <i>et al.</i> 2000; Bairlein <i>et al.</i> 2001; Lehikoinen <i>et al.</i> 2004)
North America; Cayuga Lake Basin, NY	1932-1993	52 species spring migrants	0.8 to -9.6 days/decade	(Butler 2003)
North America; Urbana, IL	1976-2002	8 spring Neotropical warbler species	2.4 to -8.6 days/decade	(Strode 2003)
Europe; Oxfordshire, England	1971-2000	20 species spring long-distance migrants	0.4 to -6.7 days/decade	(Cotton 2003)
North America; Middleborough, MA	1970-2002	16 species spring migrant birds	-2.6 to -10.0 days/decade	(Ledneva <i>et al.</i> 2004)
Europe; Ottenby, Sweden	1971-2002	36 species spring migrant birds	2.1 to -3.0 days/decade	(Stervander <i>et al.</i> 2005)
Europe-wide	1980-2002	Pied flycatcher egg-laying at 27 locations	-1.7 to -4.6 days/decade	(Both <i>et al.</i> 2004)
Australia	1970-1999	11 migratory birds	9 species earlier arrival	(Green <i>et al.</i> 2002)
Australia	1984-2003	5 migratory birds	1 species earlier arrival	(Chambers <i>et al.</i> 2005)
Europe, North America	Past 30-60 years	Numerous bird species	Earlier breeding by 1.9-4.8 days/decade	(Dunn 2004)
UK, Poland	Past 25 years	Amphibians	Earlier breeding	(Beebee 1995; Tryjanowski <i>et al.</i> 2003)

1  
2 Records of the return dates of migrant birds have shown change in recent decades associated with  
3 changes in temperature in wintering or breeding grounds or on the migration route (Tryjanowski  
4 2002; Butler 2003; Cotton 2003; Huppopp and Huppopp 2003). Different measurement methods, such  
5 as first observed individual, beginning of sustained migratory period, or median of the migratory  
6 period, provide different information about the natural history of species (Sokolov *et al.* 1998;  
7 Sparks and Braslavskaja 2001; Huppopp and Huppopp 2003; Tryjanowski *et al.* 2005). A recent meta-  
8 analysis of arrival dates (Lehikoinen *et al.* 2004) showed strong evidence of earlier arrival (of 983  
9 series 39% were significantly earlier and only 2% significantly later for first arrival dates).

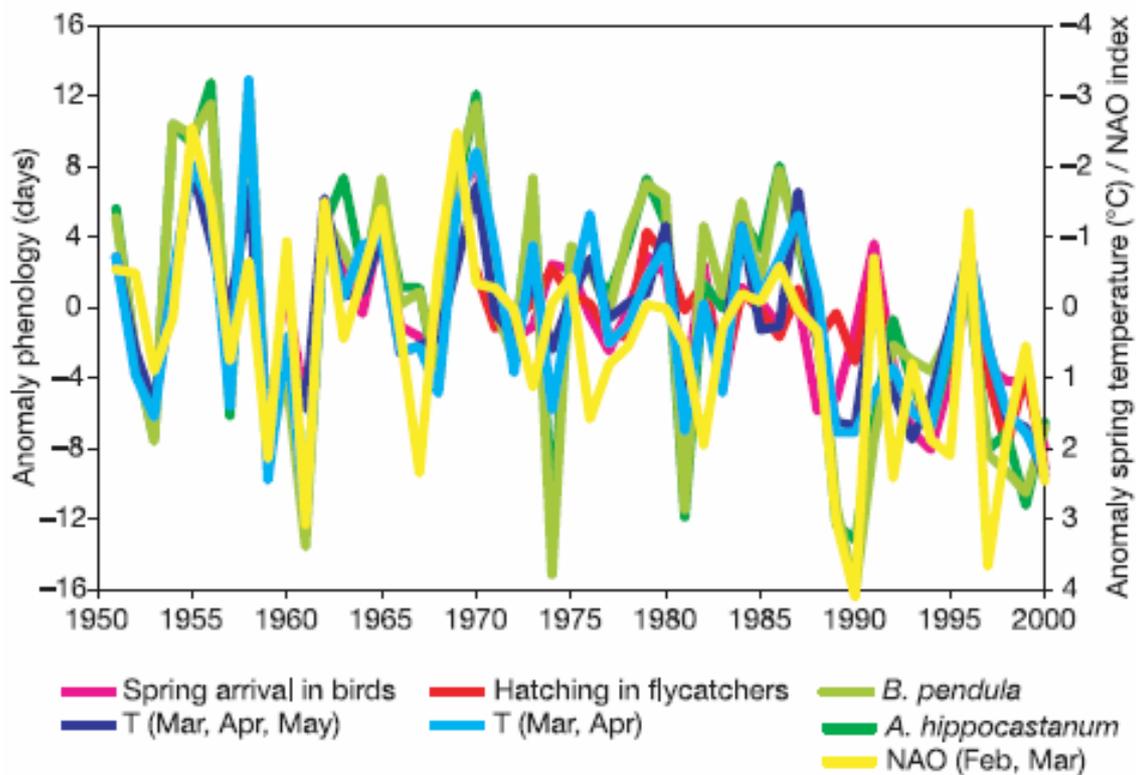
10  
11 Several studies have reported an advance in egg-laying dates in birds (Hussell 2003; Dunn 2004).  
12 The confidence in such studies is enhanced where the data cover a period of both local cooling and  
13 warming or are multinational and include sites experiencing both localised warming and cooling.  
14 Flycatchers in Europe (Both *et al.* 2004) provide an example where trend in egg-laying dates matches  
15 trends in local temperatures. Fewer examples are reported of phenological change in mammals.  
16 There are examples of altered phenology at higher altitude and latitude, for example the appearance  
17 of marmots (Inouye *et al.* 2000) and changes in the phenology of reindeer (Post, reindeer). In the  
18 Yukon, earlier breeding of pikas has been reported (Franken and Hik 2004). In amphibians there  
19 have been numerous reports of advances in mating or calling related to temperature (Gibbs and  
20 Breisch 2001; Tryjanowski *et al.* 2003). Changes in the length of the tadpole phase of the common  
21 toad were reported by Reading (Reading 2003). Despite the bulk of evidence in support of earlier  
22 breeding activity as a response to temperature, counter examples do exist (Blaustein *et al.* 2001).  
23 Advancement in the phenology of butterflies has been reported from a number of national (Roy and  
24 Sparks 2000) and local studies (Forister and Shapiro 2003; Stefanescu *et al.* 2003). There is a  
25 growing literature indicating earlier activity in other invertebrates including crickets, aphids, and  
26 hoverflies (Hickling *et al.* 2005; Newman 2005).

27  
28 *Uncertainties and Variations.* Shifts in spring activities differ by species and by time of season with  
29 early-season plants species exhibiting the stronger reactions (Abu-Asab *et al.* 2001; Menzel *et al.*  
30 2001; Fitter and Fitter 2002; Sparks and Menzel 2002; Menzel 2003). Similarly, short-distance  
31 migrating birds, which tend to migrate early in the season, often exhibit a trend towards earlier  
32 arrival while the response of later-arriving long-distance migrants is more complex, with many  
33 species showing no change or even delayed arrival (Butler 2003; Strode 2003). Annual plants  
34 respond more strongly than congeneric perennials, insect-pollinated plants more than wind-  
35 pollinated plants, woody plants less than herbaceous plants (Fitter and Fitter 2002), but there are no  
36 differences between Raunkiaer life-forms or different origins (Penuelas *et al.* 2002). Small-scale  
37 spatial variability may be due to microclimate, land cover, genetic differentiation and other non-  
38 climate drivers (Menzel *et al.* 2001; Menzel 2002). In Switzerland, the proportion of stations with  
39 advancing onset of spring events increases with altitude (Defila and Clot 2001). Geographical  
40 differences are evident, e.g., for both plants and birds in Southeast Europe by later bird arrival in  
41 the Slovak Republic (Sparks *et al.* 1999) and later start of the growing season (Menzel and Fabian  
42 1999). Spring advance, being more pronounced in maritime western and central Europe than in the  
43 continental east (Ahas *et al.* 2002; Schleip *et al.* 2005), is associated with higher spatial variability  
44 (Menzel *et al.* 2006).

45  
46 Detection of changes depends on the underlying time-frame of observations: longer series covering  
47 the last century also include periods of later onset. Earlier spring events and a longer growing  
48 season in Europe is most apparent for time-series ending in the mid 1980s or later (Schaber 2002;  
49 Scheifinger *et al.* 2002; Dose and Menzel 2004; Menzel and Dose 2005; Schleip *et al.* 2005), which  
50 matches turning points in the respective spring temperature series (Dose and Menzel 2006).

51

1 *Signal*. Spring phenology is sensitive to climate and local weather (Sparks *et al.* 1999; Lucht *et al.*  
 2 2002; Menzel 2003). In contrast to autumn phenology, the spring climate signal is fairly well  
 3 understood: nearly all spring changes in plants, including agricultural crops (Estrella *et al.* 2006)  
 4 correlate with spring temperatures in the preceding months. Alpine species are also partly sensitive  
 5 to photoperiod (Keller and Korner 2003) or amount of snow pack (Inouye *et al.* 2002). For many  
 6 birds, spring temperatures and weather conditions on wintering grounds and for some birds, late  
 7 summer and/or autumn temperatures and weather on the breeding grounds influence the timing of  
 8 migration. The speed and pattern (Menzel and Dose 2005) as well as recent trends of spring events  
 9 in European plants has changed consistently with changes seen in the North Atlantic Oscillation  
 10 (NAO) index (Chmielewski and Rotzer 2001; Scheifinger *et al.* 2002; Walther *et al.* 2002; Menzel  
 11 2003). However, directions of species changes corresponding to NAO changes can differ across  
 12 Europe (Hubalek 2003; Kanuscak *et al.* 2004). Spring phenological changes in birds and plants and  
 13 their triggering by spring temperature are often similar, as described in some cross-system studies  
 14 (Walther *et al.* 2002) (Fig. 1.4).



37 **Fig. 1.4:** Anomalies of different phenological phases in Germany (spring arrival in birds, island of  
 38 Helgoland, North Sea; hatching in flycatchers, Northern Germany; national mean onset of leaf  
 39 unfolding of *Aesculus hippocastanum* and *Betula pendula*, negative=earlier), anomalies of mean  
 40 spring air temperature *T* (35 climate stations (Menzel *et al.* 2003) and NAO index (by Jones,  
 41 <http://www.cru.uea.ac.uk/cru/data/nao.htm>). After (Walther *et al.* 2002).

44 1.3.5.3 Changes in reproduction

46 Several studies report evidence for climate change effects not only on timing and duration of the  
 47 pollen season (see 1.3.5.5), but also on pollen amounts (Beggs 2004). Among mammals, polar bear  
 48 body condition and reproductive success have declined in areas that have become ice-free for  
 49 prolonged periods, where the time available for hunting has been reduced (Derocher *et al.* 2004).

51 1.3.5.4 Changes in species distribution

1  
2 Many studies focusing on species abundances and distributions corroborate predicted systematic  
3 shifts related to changes in climatic regimes, often via species-specific physiological thresholds of  
4 temperature and precipitation tolerance. Habitat loss and fragmentation may also influence these  
5 shifts; however, temperature is likely to be the main driver if different types of species in many  
6 different areas or species throughout broad regions shift in a coordinated and systematic manner. A  
7 certain inherent resilience of treeline forests is reported and the magnitude of elevational shifts of  
8 alpine plant species lags behind the isothermal shift (Walther *et al.* 2005), whereas some butterflies  
9 appear to track decadal warming quickly (Parmesan *et al.* 1999). The survival of different bird  
10 species wintering in Europe has increased. Many species have recently expanded their ranges along  
11 the poleward boundaries as conditions in these boundary habitats become less marginal (Thomas *et*  
12 *al.* 2001).

13  
14 Changes in the distribution of species have occurred across a wide range of taxonomic groups and  
15 geographical locations during the 20<sup>th</sup> century (Table 1.10). Over the past decades a poleward  
16 extension of various plant species has been observed, which is likely attributable to increases in  
17 temperatures (Parmesan and Yohe 2003). One cause of these expansions is increased survivorship  
18 (Crozier 2004). Many Arctic and tundra communities are affected and have been replaced by trees  
19 and dwarf shrubs (Molau and Alatalo 1998; ACIA 2004). In north-western Europe, e.g., in the  
20 Netherlands (Tamis *et al.* 2001) and central Norway (EEA 2004), thermophilic (warmth-requiring)  
21 plant species have become significantly more frequent compared with 30 years ago. In contrast,  
22 there has been a small decline in the presence of traditionally cold-tolerant species. The changes in  
23 composition are the result of the migration of thermophilic species into these new areas, but also  
24 due to an increased abundance of these species in current locations.

25  
26 Altitudinal shifts of vegetation are well-documented (Dobbertin *et al.* 2005; Walther *et al.* 2005)  
27 (see Tab. 1.10). In the Alps, over the past 60 years spruce and pine species have migrated upward  
28 into the sub-alpine region (Pauli *et al.* 2001) and sub-alpine shrubs now grow on the summits  
29 (Theurillat and Guisan 2001). The movement upwards in elevation by lower elevational species has  
30 often proven detrimental to the endemic species already occurring in the higher locations. While  
31 species richness has increased in some places, it has declined in others (Wearne and Morgan 2001;  
32 Cuevas 2002; Klanderud and Birks 2003). In some places, the position of treeline has not extended  
33 up in elevation in the last half-century (Cullen *et al.* 2001; Masek 2001; Klasner and Fagre 2002),  
34 which may be due to time-lag effects owing to poor seed production/dispersal or to the presence of  
35 “surrogate habitats” with special microclimate. In mountainous regions, climate is the main driver  
36 of species composition, and human influence is relatively low, despite grazing, logging and  
37 firewood collection. Species that are often endemic and of high importance for plant diversity (Vare  
38 *et al.* 2003) are vulnerable to climate change most likely because of enhanced response to higher  
39 CO<sub>2</sub> levels, characteristic small climatic ranges, severe climatic conditions and small isolated  
40 populations (Pauli *et al.* 2003) and the absence of suitable areas at higher elevations in which to  
41 migrate.

42

43 **Table 1.10: Evidence of significant recent range shifts poleward and to higher elevation.**

Location	Species/Indicator	Observed changes due to increased temperature (if nothing else stated)	Author
California coast	Spittlebug	Northward range shift	(Karban and Strauss 2004)
Sweden	Tick ( <i>Ixodes ricinus</i> )	Northward expansion 1982-1996	(Lindgren <i>et al.</i> 2000)
Eastern Washington, USA	Sachem Butterfly ( <i>Atalopedes campestris</i> )	Range expansion with increased minimum temperature	(Crozier 2004)

Britain	Speckled wood ( <i>Pararge aegeria</i> )	Expanded N. margin, at 0.51 to 0.93 km/y, depending on habitat availability	(Hill <i>et al.</i> 2001)
Britain	4 northern butterflies	40 m mean increase in elevation, pre-1970 to 1995-99	(Hill <i>et al.</i> 2002)
Britain	37 dragonfly and damselfly species	36 out of 37 species shifted northwards (mean 84 km), 1960-70 to 1985-95	(Hickling <i>et al.</i> 2005)
Czech Republic	15 of 120 butterfly species	uphill shifts in last 40 years	(Konvicka <i>et al.</i> 2003)
Poland	White stork ( <i>Ciconia ciconia</i> )	Range expansions in elevation, 240 m during last seventy years	(Tryjanowski <i>et al.</i> 2005)
Australia	3 Macropods & 4 feral mammal species	Range expansions up in elevation	(Green, 2002, alpine)
Australia	Grey-headed Flying Fox	Contraction of southern boundary poleward by 750 km since 1930s	(Tidemann, 1999, flying foxes)
Senegal, West Africa	126 tree and shrub species	35-50 km latitudinal shift of ecological zones in the period 1945-1993 due to decrease in annual precipitation	(Gonzalez 2001)
Sweden, Spain, New Zealand, California	Treeline	Advancement towards higher altitudes	(Meshinev <i>et al.</i> 2000; Kullman 2002; Penuelas and Boada 2003; Millar and Herdman 2004)
Canada	Forest-Tundra line	12 km/year northward shift by NDVI and land-surface temperature data	(Fillol and Royer 2005)
Alaska	Arctic shrub vegetation	Expansion of shrubs in previously shrub-free areas	(Sturm and Liston 2003)
European Alps	Alpine summit vegetation	Elevational shift, increased species richness on mountain tops	(Walther <i>et al.</i> 2005)
Montana, US	Arctic-alpine species	Decline at the southern margin of range	(Lesica and McCune 2004)
Germany, Scandinavia	English Holly ( <i>Ilex aquifolium</i> )	Poleward shift of northern margin due to increasing winter temperatures	(Walther <i>et al.</i> 2005)

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*Climate-linked extinctions.* Determining the exact cause or causes of extinction can be difficult. As the time-horizon lengthens, however, more extinctions are likely to occur (Thomas *et al.* 2004). Currently about 20% of the bird species are extinction prone, while around 5% are already functionally extinct (e.g., small inbreed populations) (Sekercioglu *et al.* 2004). The extinction process in declining species is reflected by fragmented distributions (Wilson *et al.* 2004). Prominent examples for declines in populations and subsequent extinction/extirpation (Ron *et al.* 2003) are found in amphibians around the world (Pounds *et al.* 2006). In Puerto Rico, a synergistic interaction between drought and disease has been noted (Burrowes *et al.* 2004). In Central and South America, the synergy between UVB radiation and other factors, such as acidification, have been hypothesized (Middleton *et al.* 2001). Climate variability (of both temperature and precipitation) is unlikely to be the direct cause of amphibian decline (Alexander and Eischeid 2001), but it has been found to have significant impact on the extinction of the butterfly *Euphydryas editha* (McLaughlin *et al.* 2002) and *Euphydryas editha bayensis* (McLaughlin *et al.* 2002).

*Climate-linked invasions.* Fluctuation in resource availability, which can be driven by climate variability, has been identified as the key factor controlling the susceptibility of an environment to invasion by non-resident species (Davis *et al.* 2000). The clearest evidence for climate variability triggering an invasion occurs where a suite of species with different histories of introduction spread

1 en-masse during periods of climatic amelioration (Walther 2000). A prominent example is  
2 thermophilous plants that spread from gardens into the surrounding countryside in southern  
3 Switzerland (Walther 2000; Walther *et al.* 2002), and exotic thermophilous plants spreading into  
4 the native flora of Spain and Ireland (Pilcher and Hall 2001; Sobrino *et al.* 2001). Elevated CO<sub>2</sub>  
5 might also contribute to the spread of weedy, non-indigenous plants (Hattenschwiler and Korner  
6 2003).

#### 7 8 1.3.5.5 *Species community changes and ecosystem processes*

9  
10 In many parts of the world, including Europe, species composition has changed (Walther *et al.*  
11 2002), partly due to invasions and distributional changes (see 1.3.5.4). The assemblages of species  
12 in ecological communities reflect interactions among organisms as well as between organisms and  
13 the abiotic environment. Climatic change, enhanced CO<sub>2</sub> levels or extreme climatic events can alter  
14 community composition as species differentially track their climatic tolerances. If this is  
15 asymmetrical with species invading faster than resident species are receding, species diversity may  
16 increased in certain regions (e.g., northwestern Europe) due to a northward movement of southern  
17 species, whereas the effect on cold-tolerant species is still limited (Tamis *et al.* 2001; EEA 2004)  
18 (see 1.3.5.4). In non-fragmented Amazon forests, direct effects of CO<sub>2</sub> on photosynthesis, as well as  
19 faster forest turnover rates, may have driven non-linear composition response with a substantial  
20 increase in density and basal area of lianas over the last 2 decades (Phillips *et al.* 2002). Although  
21 many species-community changes are also attributable to landscape fragmentation, habitat  
22 modification, and other non-climate drivers, many studies show a high correlation between changes  
23 in species composition and recent climate change, also via frequency of weather-based disturbances  
24 (Hughes 2000; Pauli *et al.* 2001; Parmesan and Yohe 2003). Examples of altered or stable  
25 synchrony in ecosystems via multi-species interactions are still not abundant. Visser and Holleman  
26 (Visser and Holleman 2001) found different responses in the Pedunculate Oak-Winter Moth-Tit  
27 food chain compared to Buse (Buse *et al.* 1999) and van Noordwijk (van Noordwijk *et al.* 1995).

#### 28 29 1.3.5.6 *Species evolutionary processes*

30  
31 Recent evolutionary responses to climate change have been reviewed by Thomas (Munich Re  
32 Group 2005). Changes have taken place in the plants preferred for egg-laying and feeding of  
33 butterflies, e.g., a broadened diet facilitated the colonisation of new habitats during range extension  
34 in Britain (Thomas *et al.* 2001). The pitcher-plant mosquito in the USA has prolonged development  
35 time in late summer by the evolution of changed responses to daylength (Bradshaw and Holzapfel  
36 2001; Bradshaw *et al.* 2003). The blackcap warbler has recently extended its overwintering range  
37 northwards in Europe by evolving a change in migration direction (Berthold *et al.* 2003). Insects  
38 expanding their ranges have undertaken genetically-based changes in dispersal morphology,  
39 behaviour and other life history traits, as “good colonists” have been at a selective advantage (Hill  
40 *et al.* 1999; Thomas *et al.* 2001; Hughes *et al.* 2003; Simmons and Thomas 2004). Genetic changes  
41 of *Drosophila melanogaster* in eastern coastal Australia over 20 years are likely to reflect  
42 increasingly warmer and drier conditions (Umina *et al.* 2005). Evolutionary processes are also  
43 demonstrated by reproductive phenological change associated with climate change in North  
44 American Red squirrels (Berteaux *et al.* 2004). There is no evidence so far that the temperature  
45 response rates of plants has changed over the last century (Menzel 2005).

#### 46 47 1.3.5.7 *Summary*

48  
49 The overwhelming majority of studies of terrestrial biological systems reveal notable impacts of  
50 global warming over the last 3-5 decades, which are consistent across plant and animal taxa: earlier  
51 spring and summer phenology and longer growing seasons in mid and higher latitudes, range

1 expansions at higher elevations and latitudes, some evidence for population declines at lower  
 2 elevational or latitudinal limits to species ranges, and vulnerability of species with restricted ranges,  
 3 leading to (local) extinctions. Non-climate synergistic factors can significantly limit migration and  
 4 acclimation capacities.

5  
 6 While a variety of methods have been used that provide evidence of biological change over many  
 7 ecosystems, there remains a notable lack of studies on some ecosystems particularly in tropical  
 8 regions, due to a significant lack of long-term data. Furthermore, not all processes influenced by  
 9 warming have yet been studied. Nevertheless, in the large majority of studies, the observed trends  
 10 found in species correspond to predicted changes in terms of magnitude and direction. Analyses of  
 11 regional differences in trends reveal that spatio-temporal patterns of both phenological and range  
 12 change are consistent with spatio-temporal patterns expected from observed climate change.

### 13 14 **1.3.6 Agriculture and forestry**

15  
 16 Although agriculture and forestry are known to be highly dependent on climate, little evidence of  
 17 observed changes related to regional climate changes was noted in the TAR. This is likely due to  
 18 the strong influence of non-climate factors on agriculture, and to a lesser extent, on forestry,  
 19 especially management practices and technological changes on local and regional scales, as well as  
 20 market prices and policies related to subsidies (Easterling 2003). The worldwide trends in  
 21 increasing productivity (yield per hectare) of most crops over the last 40 years, primarily due to  
 22 technological improvements in breeding, pest and disease control, fertilization, and mechanization,  
 23 also makes identifying climate change signals difficult (Hafner 2003).

#### 24 25 **1.3.6.1 Crops and livestock**

26  
 27 Changes in crop phenology provide important evidence of responses to climate (Table 1.10a). Such  
 28 changes are apparent in production of perennial crops, such as fruit trees and wine-grapes, which  
 29 are less dependent on yearly management decisions by farmers than annual crops and are also often  
 30 easier to observe. But some evidence also appears in annual crops. Phenological changes are often  
 31 observed in tandem with changes in management practices by farmers (Table 1.11b). A study in  
 32 Germany (Menzel *et al.* 2006) has revealed that between 1951 and 2004 the advance for  
 33 agricultural crops (2.1 days/decade) has been significantly less marked than for wild plants or fruit  
 34 trees (4.4 to 7.1 days/decade). All the reported studies concern Europe, where recent warming has  
 35 clearly advanced a significant part of the agricultural calendar.

36  
 37  
 38 **Table 1.11: Observed changes in agricultural crop production and livestock:(a) Phenology; (b)**  
 39 **Management practices, pests and diseases; (c) Yield; (d) Livestock.**

Location	Period	Observed Change	Author
40 a). Phenology			
Germany	1961-2000	Observed advance of stem elongation for winter rye (10 days) and emergence for maize (12 days)	(Chmielewski <i>et al.</i> 2004)
European Union	1975-2001	Advance in wheat flowering (3 weeks) computed with CGMS model	(Genovese <i>et al.</i> 2005)
Germany	1951-2000	Observed advance in cherry tree flowering (0.9 days/10 years), apple tree flowering (1.1 days/10 years) in response (-5 days/°C) to March/April temperature increase	(Menzel 2003)
Germany	1961-1990	Observed advance in beginning of growing season for fruit trees (2.3 days/10 years),	(Chmielewski <i>et al.</i> 2004)

		cherry tree blossom (2.0 days/10 years), apple tree blossom (2.2 days/ 10 years) in agreement with annual air temperature increase of 1.4°C.	
South of France	1970-2001	Observed advance of fruit tree flowering of 1 to 3 weeks for apricot and peach trees, increase in spring frost risks, and more frequent occurrence of bud fall or necrosis for sensitive apricot varieties	(Seguin <i>et al.</i> 2004)

## 1 b). Management practices, pests and diseases

Germany	1961-2000	Observed advance of seeding dates for maize and sugarbeet (10 days)	(Chmielewski <i>et al.</i> 2004)
France	last 30 years	Observed advance of maize sowing dates by 20 days in 4 INRA experimental farms	(Benoit and Torre 2004)
Finland	1965-1999	Observed advance of potato sowing date by 5 days, no change for spring cereals	(Hilden and Lethtonen 2005)
South of France	last 20 years	Observed partial shift of apple codling moth from two to three generations	(Sauphanor and Boivin 2004)

## 2 c) Yields

Rothamsted UK (Europe)	1965-1998	Observed lower hay yields, in relation with warmer summers	(Cannell <i>et al.</i> 1999)
USA county level	1982-1998	Part of overall yield increase attributed to recent cooling during growing season): 25% maize, 33 % soybean	(Lobell and Asner 2003)
IRRI field Philippines	1992-2003	Decrease of rice yield associated with increase of temperature (0.35 °C and 1.13°C for maximum and minimum respectively during 1979-2003).	(Peng <i>et al.</i> 2004)

## 3 d) Livestock

Mandalgobi station (Mongolia)	1970-2002	Decrease of measured pasture biomass by 20 to 30%	(Batimaa 2005)
Mongolia	1982-2002	Decline of NDVI of the third decade of July by 69% for the whole territory	(Erdenetuya 2004)
Asia (Tibet)	1978-2002	Observed increase in animal production related to warming in summer and annual temperature.	(Du <i>et al.</i> 2004)

4  
5  
6 Since the TAR, there has been evidence of recent trends in agro-climatic indices, particularly those  
7 with a direct relationship to temperature, such as increases in growing season length and in  
8 growing-degree-days during the crop cycle. These increases, associated with earlier last spring frost  
9 and delayed autumn frost date, are clearly apparent in temperate regions of Europe (Moonen *et al.*  
10 2002; Menzel 2003; Genovese *et al.* 2005) and a major part of North America (Robeson 2002; Feng  
11 and Hu 2004). They are especially detectable in indices applicable to wine-grape cultivation (Box  
12 1.2). In Sahelian countries, increasing temperature in combination with rainfall reduction has led to  
13 a reduced length of vegetative period no longer allowing present varieties to complete their cycle  
14 (Ben Mohamed *et al.* 2002).  
15

16 **Box 1.2: Wine and Recent Warming**

17  
18 Wine-grapes are known to be highly sensitive to climatic conditions, especially temperature  
19 (viticulture was thriving in Great Britain during the last medieval warm period). They have been  
20 used as an indicator of observed changes in agriculture related to warming trends, particularly in  
21 Europe and in some areas of North America.  
22

1 Using 30 years of data for grapevine production in Alsace, France, Duchêne (Duchene and  
2 Schneider 2005) found that the number of days with a mean daily temperature above 10°C  
3 (favourable for vine activity) in the last 70 years has increased from 170 to 210 at the end of the  
4 20<sup>th</sup> century. The increase of the heliothermal index of Huglin (Seguin *et al.* 2004) is observed for  
5 all the wine-producing areas of France. It is associated to a lower year-to-year variability in the last  
6 15 years, which provides conditions favourable for wine, in terms of both quality and stability.  
7 Jones (Jones 2005) observed similar trends in the average growing-season temperatures (April-  
8 October for the Northern Hemisphere) at the main sites of viticultural production in Europe. The  
9 same tendencies have also been found in the California, Oregon, and Washington vineyards of the  
10 U.S., Nemani (Nemani *et al.* 2001), (Jones 2005).

11  
12 Consequences of warming are already detectable in the wine quality, as shown by Duchêne  
13 (Duchene and Schneider 2005) with a gradual increase of the potential alcohol levels at harvest for  
14 Riesling in Alsace of nearly 2% volume in the last 30 years. On a worldwide level, Jones (Jones  
15 2005) has established, for 25 of the 30 analyzed regions, increasing trends of vintage ratings  
16 (average rise of 13.3 points on a 100-point scale for every 1°C warmer the growing season), with  
17 lower vintage-to-vintage variation.

18  
19 In spite of this, no detectable change in crop yield directly attributable to climate has been reported  
20 for Europe, even though model simulations exhibit a tendency to lower potential biomass with  
21 observed levels of warming (Table 1.11c). For example, the yield trend of winter wheat displays  
22 progressive growth from 2.0 t/ha in 1961 to 5.0 t/ha in 2000, with anomalies due to climate  
23 variability on the order of 0.2 t/ha (Cantelaube *et al.* 2004). The same observation is valid for Asia,  
24 where the rice production of India has grown since 1999 from 20 M tons to over 90 M tons, with  
25 only a slight decline during El Niño years when monsoon rainfall is reduced (Selvaraju 2003). A  
26 negative effect of warming for rice production observed by IRRI in The Philippines (yield loss of  
27 15% for 1C increase of growing-season minimum temperature in the dry season)(Peng *et al.* 2004)  
28 is limited to a local observation for a short time-period; a similar effect has been noted on hay yield  
29 in the UK (1C increase in July-August led to 0.33 t/ha loss) (Cannell *et al.* 1999). A study at the  
30 county level of US yields (Lobell and Asner 2003) has established a positive effect of cooler and  
31 wetter years in the Midwest and hotter and drier years in the Northwest plains. In the case of the  
32 Sahel region of Africa, warmer and drier conditions have served as a catalyst for a number of other  
33 factors that have accelerated a decline in groundnut production (Van Duivenbooden *et al.* 2002).

34  
35 Changes in crop area distribution have not been associated with regional climate trends, but  
36 enlarged areas of vineyards and forage maize in production have been selected as indicators of  
37 climate change in the UK, along with the use of irrigation water for agriculture, proportion of potato  
38 crop that is irrigated, and potato yield (Cannell *et al.* 1999).

39  
40 For livestock (Table 1.11d), one study in Tibet reports a significant relationship of improved  
41 performance with warming in high mountainous conditions (Du *et al.* 2004). On the contrary, the  
42 pasture biomass in Mongolia has been affected by the warmer and drier climate, as observed at a  
43 local station (Batimaa 2005) or at the regional scale by remote sensing (Erdenetuya 2004).

#### 44 1.3.6.2 Forestry

45  
46  
47 Here we focus on forest productivity and its contributing factors (see Section 1.3.5 for phenological  
48 aspects). The terrestrial carbon cycle is strongly linked to inter-annual climate variability. However,  
49 the rising atmospheric CO<sub>2</sub> concentration, nitrogen fertilization, lengthening of the growing season  
50 due to warming, and changed management have resulted in a steady increase in annual forest CO<sub>2</sub>  
51 storage capacity in the past few decades, which leads to a more significant net carbon uptake

1 (Nabuurs *et al.* 2002). Net primary production over the same period increased by 6% globally, with  
2 the largest increases in tropical ecosystems (Nemani *et al.* 2003). Northern vegetation activity  
3 inferred from satellite data of vegetation index has increased in magnitude by 12% in Eurasia and by  
4 8% in North America from 1981-1999. Thus the overall trend towards longer growing seasons is  
5 consistent with an increase in the 'greenness' of vegetation, for broadly continuous regions in Eurasia  
6 and in a more fragmented way in North America, reflecting changes in biological activity (Zhou *et*  
7 *al.* 2001). Analyses in China attribute increases in net primary productivity, in part, to countrywide  
8 lengthening of the growing season (Fang *et al.* 2003). Similarly, other studies find a decrease in the  
9 frost-free period in northern China by 10 days (Schwartz and Chen 2002) and advances in spring  
10 phenology (Zheng *et al.* 2002). In humid evergreen tropical forest in Costa Rica, annual growth in  
11 the period 1984-2000 varied inversely with the annual means of daily minimum temperature, because  
12 of increased respiration at night (Clark and *et al.* 2003). However, for southern Europe, an opposite  
13 trend has been detected in relation due the observed rainfall decrease (Maselli 2004), especially after  
14 the severe drought episode of 2003 (Gobron *et al.* 2005; Lobo and Maisongrande 2005).

15  
16 Climate warming can also change the disturbance regime of forests by increasing the range  
17 extension of some damaging insects as observed during the last 20 years for bark beetles in USA  
18 (Williams and Liebhold 2002) or pine processionary moth in Europe (Battisti *et al.* 2004). The  
19 latter has displayed an observed northward shift of 27 km/decade near Paris, a 70m/decade upward  
20 shift in altitude for southern slopes and 30m/decade for northern slopes in Italian mountains.

21  
22 Trends in disturbance resulting from forest fires are still a subject of controversy. While the  
23 increase of outdoor fires in England and Wales between 1965 and 1998 may be attributable to a  
24 trend toward warmer and drier summer conditions (Cannell *et al.* 1999), McKenzie (McKenzie *et*  
25 *al.* 2004) has established that, in spite of management acting to reduce fuel load in forests, climate  
26 variability is the dominant factor affecting large wildfires. This is confirmed by an analysis of forest  
27 fires in Siberia between 1989 and 1999 (Conard *et al.* 2002), which detected the significant impacts  
28 of two large fires in 1996 and 1998, resulting in 13 million ha burned and the emission of 14-20%  
29 of the annual global carbon emission from forest fires. Also, repeated large forest fires during the  
30 warm season in recent years in the Mediterranean region and North Africa, as well as in California,  
31 have been linked to drought episodes. One study for forest fires in Canada (Gillett *et al.* 2004)  
32 found that the observed increase in burned areas during the last 40 years, in spite of improved fire-  
33 fighting techniques, is in agreement with simulated warming from a GCM model. About half of the  
34 trend towards increasing area burned may be attributed to climate change as the result of a  
35 statistical model. However, this finding is not in agreement with another study (Bergeron *et al.*  
36 2004), which found that 1940 to 1970 was a period of relatively low fire frequency in Canada and a  
37 tendency for a recent decrease of fires in Eastern Canada.

### 38 39 1.3.6.3 Evidence of adaptation and vulnerability

40  
41 There is little documented evidence of adaptation to regional climate trends in agriculture and  
42 forestry, with only a few studies related to the shift of sowing dates of annual crops. There is even  
43 less evidence related to food supply. In regard to vulnerability, evidence of observed effects  
44 (changes in planting or shifts in distribution) studies have primarily focused on crops in developed  
45 countries, and not on effects in relation to subsistence agriculture in rural populations in developing  
46 countries.

47  
48 Changes in vulnerability are difficult to assess in relation to recent changes in mean temperature at  
49 the decadal scale. Vulnerability in these sectors appears to be high in the case of extreme events or  
50 exceptional episodes, such as the summer of 2003 in Europe. The extreme warming (which was  
51 close to levels projected by end-of-century GCM climate change scenarios) resulted in the strongest

1 negative deviation in crop production from the long-term trend in the last 43 years (FAO 2004).  
2 Greece, Portugal, Italy and especially France suffered yield decreases of up to 30%.

3  
4 Global crop modelling studies have projected that agriculture in developed countries will mostly  
5 benefit from climate change at least in the near-term, while developing nations, for the most part,  
6 will experience declines in production (Parry *et al.* 2004). The observed trends tend to confirm the  
7 model simulations. Regions in North America (Lobell and Asner 2003) and Northern Europe, apart  
8 from 2003 (Genovese *et al.* 2005), in general, appear to have experienced more favourable growing  
9 conditions, but the first study leads to predict a reduction of 17 % in corn and soybean for each 1°  
10 increase of growing season temperature. Regions such as the Sahel (Van Duivenbooden *et al.*  
11 2002) have experienced changes that have been unfavourable to crop production, whilst the local  
12 experiment in Philippines (Peng *et al.* 2004) indicates a potential tendency for reduced rice  
13 production with warming in tropical countries.

#### 14 1.3.6.4 Summary

15  
16 Trends in individual climate variables or their combination into agro-climatic indicators show that  
17 there is an advance in phenology in large parts of North America and Europe, which has been  
18 attributed to recent regional warming. In temperate regions, there are clear signals of reduced risk  
19 of frost, longer growing season duration, increased biomass, higher quality (for grapevines, a  
20 climate-sensitive crop), insect expansion, and increased forest-fire occurrence that are in agreement  
21 with regional warming. These effects are hard to detect in aggregate agricultural statistics because  
22 of the influence of non-climate factors. Though the present effects are of limited economic  
23 consequence and appear to lie within the ability of the sectors to adapt, both the agriculture and  
24 forestry sectors show vulnerability to recent extreme heat and drought events.

#### 25 1.3.7 Human Health

26  
27 Here we evaluate evidence regarding observed changes in human health and regional climate  
28 change. These observed changes are related to temperature trends and extremes in nearly all cases  
29 and their resultant impacts on infectious diseases, noncommunicable diseases associated with heat  
30 and cold stress, or environmental allergens (See Chapter 8).

31  
32 The superposition of natural climate variability on greenhouse gas-induced warming can produce  
33 fluctuations that may be key drivers of interannual variability in many parts of the world. Extremes  
34 of temperature and rainfall, sometimes associated with ENSO can be associated with the  
35 transmission and occurrence of certain diseases in certain locations (Kovats *et al.* 2001). Climate  
36 extremes in temperature and precipitation have direct impacts, such as heat and cold extremes,  
37 which can result in well-described impacts on mortality (8.2.1). Additionally, temperature and  
38 rainfall variability can be an important determinants of the transmission of vector borne diseases.  
39 Githeko and Ndegwa (Githeko and Ndegwa 2001) have shown, for example, how unusually high  
40 temperatures in the normally cool highlands of Kenya have been favourable to malaria outbreaks.

41  
42 There is a wide range of driving forces that can affect and modify the impact of climate change on  
43 human health indicators. Consideration of reported trends in a given disease and the attribution to  
44 climate change needs to take into account three possible conditions:

- 45 • The change in disease incidence is real and due to changes in important non-climate  
46 determinants which include social factors, such as human population density and behaviour;  
47 housing facilities; public health facilities (e.g., water supply and general infrastructure, waste  
48 management and vector-control programs); use of land for food, fuel and fibre supply; and  
49

1 results of adaptation (e.g., drug use as well as insecticide use), as well as changed resistance of  
2 organisms and vector species Sutherst (Sutherst 2004), Githeko and Woodward (Githeko and  
3 Woodward 2003.), Molyneux (Molyneux 2003), and Tillman (Tillman *et al.* 2001 ).

- 4 • The change in disease incidence is real and due to changes in a climate factors, once all non-  
5 climate determinants have been considered and excluded as the main explanation (see for  
6 example (Purse *et al.* 2006). Patz (Patz *et al.* 2005) notes that changes in land use and land  
7 cover can affect the local climate and ecosystems and should be considered when linking  
8 climate and health.
- 9 • That the changes in disease incidence are not real, but only due to increased reporting.

#### 11 1.3.7.1 *Analysis of evidence regarding ENSO and human health*

12  
13 Some climate and health studies have addressed the issue of climate variability, especially the  
14 ENSO phenomena (see Chapter 8) while only a very few have investigated the health effects of  
15 observed climate change. For example, studies in Thailand have established that there is a  
16 significant complex, non-linear association between El Nino, climate variables and dengue fever  
17 and dengue haemorrhagic fever (DHF) (Koelle and Pascual 2004; Cazelles *et al.* 2005). The effect  
18 of ENSO on the risk of malaria epidemics has been well established in parts of South Asia and  
19 South America, and also for cholera in some coastal regions (Lipp *et al.* 2002; Kovats *et al.* 2003).  
20 Rodo et al (Rodo *et al.* 2002) found an increased role of interannual climate variability on the  
21 temporal dynamics of cholera in Bangladesh, with a more robust relationship in recent times  
22 accounting sometimes for over 70% of variability at selected intervals between the more variable  
23 and intense recent El Niño events and cholera prevalence (Rodo *et al.* 2002). ENSO-related SST  
24 changes in bounded regions of the Indian Ocean and the Bay of Bengal may be associated with  
25 flooding over Bangladesh in the last decades of the 20<sup>th</sup> century and with increases in  
26 transmissibility for cholera at interannual timescales (Koelle and Pascual 2004). Variability in sea  
27 surface temperatures is associated with higher incidence of toxin-related illnesses, such as cholera  
28 and possibly shellfish poisoning (Patz *et al.* 1996).

#### 30 1.3.7.2 *Trends in vector-borne diseases*

31  
32 Vector-borne diseases are known to be sensitive to temperature and rainfall factors (as shown by  
33 the ENSO effects discussed above). Consideration of these interactions suggests that warmer  
34 temperature is likely to have two major kinds of closely related, potentially detectable, outcomes:  
35 changes in vectors *per se*, and changes in vector-borne disease outcomes. Insect and tick vectors  
36 would be expected to respond to changes in climate like other cold-blooded terrestrial species.  
37 There is some evidence that this is occurring in relation to three vector-borne diseases or their  
38 vectors.

39  
40 *Lyme disease.* Changes in the latitudinal spread and abundance of Lyme disease vectors in  
41 relationship to milder winters have been well-documented in Sweden (Lindgren *et al.* 2000;  
42 Lindgren and Gustafson 2001), although results may have been influenced by changes due to  
43 reporting and changes in human behaviour.

44  
45 *Tick-borne encephalitis (TBE).* Increase in TBE in Sweden since the mid-1980s may have been  
46 caused by milder climate in this period, permitting an increase in tick abundance (Lindgren and  
47 Gustafson 2001), but other explanations cannot be ruled out (Randolph 2001).

48 *Malaria.* There is still much uncertainty about the potential impact of climate change on malaria  
49 disease at a local scale. In particular, the role of observed climate change on the geographical  
50 distribution of malaria and its transmission intensity in highland areas remains controversial.

51 Malaria incidence has increased since 1970s at some sites in East Africa. Chen *et al.* (Chen *et al.*

1 2006), have demonstrated the recent spread of falciparum malaria and its vector *Anopheles*  
2 *arabiensis* in highland areas of Kenya that were malaria-free as recently as 20 years ago. It has yet  
3 to be proven whether this is due solely to warming of the environment. A range of studies have  
4 demonstrated the importance of temperature variability in malaria transmission in these highland  
5 sites (Bouma, 2003; Abeku *et al.*, 2003; Zhou *et al.*, 2004; Zhou *et al.*, 2005) (see 8.2.8.2 for  
6 detailed discussion). While a few studies have shown the effect of a long-term upward trends in  
7 temperature on malaria in some highland sites (e.g. Tulu 1996), other studies indicate that increase  
8 in resistance of the malaria parasite to drugs, decrease in vector-control activities, and ecological  
9 changes may have been be the most likely driving forces behind the malaria resurgence in recent  
10 years. Thus, while climate is a major limiting factor in the spatial and temporal distribution of  
11 malaria, many non-climatic factors (drug resistance and HIV prevalence, and secondarily, cross-  
12 border people movements, agricultural activities, emergence of insecticide resistance and the use of  
13 DDT for indoor residual spraying) may alter or override the effects of climate (Craig *et al.* 2004;  
14 Craig *et al.* 2004; Barnes and Durrheim 2005).

15  
16 There is a shortage of concurrent detailed and long-term historical observations of climate and  
17 malaria. Good quality time-series of malaria records in the East African and the Horn of Africa  
18 highlands are too short to address the early effects of climate change. Very few sites have longer  
19 data series, and the evidence on the role of climate change is unresolved (Hay *et al.*, 2002a; Hay *et al.*  
20 *et al.*, 2002b; Patz *et al.* 2002; Shanks *et al.*, 2002), although a recent study has confirmed warming  
21 trends at these sites (Pascal *et al.* 2006).

#### 22 23 1.3.7.3 *Effects of trends in heat and cold stress*

24  
25 Episodes of extreme heat or cold have been associated with increased mortality independent of  
26 season and populations (Huynen *et al.* 2001; Curriero *et al.* 2002). There is evidence of recent  
27 increases in mean surface temperatures and in the number of days with high temperatures, with the  
28 extent of change varying by region (Karl and Trenberth 2003; Luterbacher *et al.* 2004; Schar *et al.*  
29 2004)[see WGI]. This increase in heatwave exposures has been associated with excess mortality, as  
30 was dramatically illustrated in the 2003 heatwave in western and Central Europe, which was the  
31 hottest summer since 1500 (Luterbacher *et al.* 2004). France was most affected, and more than  
32 14000 excess deaths are estimated to have occurred there during the heat wave (Insitute de Veille  
33 Sanitaire 2003; Vandentorren *et al.* 2004).

34  
35 In general, high-income populations are become less sensitive to both heat and cold. Studies in  
36 Europe and in the United States of mortality over the past 30 to 40 years found evidence of  
37 declining death rates during summer months, which was attributed to increased use of air  
38 conditioning, improved health care, and increased public awareness of the risks of exposure to high  
39 ambient temperatures (Davis *et al.* 2003; Davis *et al.* 2003; Donaldson *et al.* 2003). Declines in  
40 winter mortality are apparent in many countries due to both a reduction in cold days, as well as a  
41 decreased response to cold.

#### 42 43 1.3.7.4 *Emerging food- and water-borne diseases*

44  
45 Food- and water-borne diseases (WBD) are major adverse issues associated with warming and  
46 extreme precipitation events. Bacterial infectious diseases are sometimes sensitive to temperature,  
47 e.g., salmonellosis incidence was associated with monthly temperatures in Australia (D'Souza *et al.*  
48 2004). In US and Canada, there is a reported increase in outbreaks of *Escherichia coli* 0157:H7 and  
49 *Cryptosporidium* from 1950 through 2000, although this cannot be attributed to climate change  
50 (Charron *et al.* 2004). Water-borne disease outbreaks are often triggered by extreme rainfall events  
51 (Casman *et al.* 2001; Curriero *et al.* 2001; Rose *et al.* 2002; Diergaardt *et al.* 2004) but, again, no

1 attribution to longer-term trends in climate has been attempted.

2  
3 *Harmful Algal Blooms.* There also appears to be an increasing trend in harmful algal blooms  
4 (HABs) in coastal waters. Proliferation of harmful algal blooms poses a threat to human health in  
5 some regions of the world. Increases in 'red tides' and other HABs during the past 50 yr on both the  
6 Atlantic and Pacific coasts of Canada suggest that global-scale factors, such as climate change and  
7 increased international shipping trade, can be the main driving forces (Mudie *et al.*, 2002; Van  
8 Dolah, 2000). However, most of the time, the origin and climatic suitability conditions for red tide  
9 proliferations are not well-known (Yang, ZB; Hodgkiss, IJ (2004), such as for *Fibrocapsa japonica*  
10 (De Boer *et al.*, 2005), *Gymnodinium catenatum*, *Pyrodinium bahamense* var. *compressum*, and  
11 recently *Cochlodinium* cf. *catenatum*. The variability and near-concurrence of species blooms in the  
12 modern (past 60 yr) record is unmatched in the past, according to the examination of the Holocene  
13 history of harmful phytoplankton species and suggests disequilibrium of the natural ecosystem  
14 structure (Mudie *et al.*, 2002) and a climate change effect (via surface temperature and storminess)  
15 as the main driving force stimulating blooms.

#### 16 17 1.3.7.5 *Pollen- and dust-related diseases*

18  
19 There is evidence that observed climate change is affecting the timing of the onset of pollen  
20 production (Van Vliet *et al.* 2002; WHO 2003; Beggs 2004) (see 1.3.5). Studies, mostly from  
21 Europe, indicate the seasonal onset of some important allergens have become earlier in recent  
22 decades, and such shifts are consistent with observed changes in climate (Teranishi *et al.* 2000;  
23 Rasmussen 2002; Emberlin *et al.* 2003). However, there is no good evidence that temperature  
24 changes have increased pollen abundance or allergenicity, although laboratory and field studies  
25 suggest that increased CO<sub>2</sub> may facilitate increased pollen abundance (Ziska and Caufield 2000).  
26 Pollen abundance, however, is more strongly associated with land-use change and farming practices  
27 than to weather. Changing agricultural practices, such as the replacement of haymaking in favour of  
28 silage production, have also affected the grass pollen season in Europe. The impact on health of  
29 dust and dust storms has not been well described in the literature. Prospero and Lamb (Prospero,  
30 2003, African dust) have reported on African droughts and dust transported across the Atlantic to  
31 the Caribbean, while Gyan (Gyan *et al.* 2003) reported a dramatic increase in respiratory disease in  
32 the Caribbean attributed to increase in Sahara dust, which has in turn, has been linked to climate  
33 change.

#### 34 35 1.3.7.6 *Summary*

36  
37 While there is little evidence of climate change currently having widespread significant detectable  
38 effects on human health, there is some evidence that shows increased incidence and range of some  
39 vector-borne diseases and dust and pollen-borne diseases. Changes in cholera incidence in  
40 Bangladesh have been related to changes in the El Nino-Southern oscillation. Evidence linking  
41 climate changes with famine-related nutrition is inconclusive. An increase in variability of high  
42 temperature has been associated with excess mortality during the 2003 heatwave in Europe,  
43 although, in general, adaptation to high temperature via air-conditioning has contributed to declines  
44 in death rates during the summer in the U.S. and Europe over the past 30-40 years.

#### 45 46 47 1.3.8 *Disasters and hazards*

48  
49 The rapid onset meteorological hazards with the potential to cause the greatest destruction to  
50 property and lives include extreme river floods, intense tropical & extratropical cyclone windstorms  
51 (along with their associated coastal storm surges), as well as the most severe supercell

1 thunderstorms. Here we assess the evidence for a change in the frequency, geography and/or  
2 severity of these high energy events.

3  
4 By definition the extreme events under consideration here are rare events, with return periods in a  
5 location typically in excess of 10-20 years – as the built environment is generally sited and  
6 designed to withstand the impacts of more frequent extremes. Given that the strong rise in global  
7 temperatures only began in the 1970s, it is difficult to demonstrate statistically a change in the  
8 occurrence of extreme floods and storms (with return periods of 20 years or more) simply from the  
9 recent historical record (Frei and Schar 2001). In the quest to identify a change in extreme flood and  
10 storm return periods: Data may be pooled from independent and uncorrelated locations that share  
11 common hazard characteristics so as to search for changes in occurrence across all of them  
12 collectively. A search for a statistically significant change in occurrence characteristics of  
13 relatively high frequency events (with return periods <5 years) can be used to infer changes at  
14 longer return periods.

#### 15 16 1.3.8.1 *Extreme river floods*

17  
18 In the most comprehensive available global study, Kundzewicz (Kundzewicz 2004) examined  
19 worldwide information on annual extreme daily flows from 195 rivers, principally in North  
20 America and Europe, and did not find any consistent trends with the number of rivers showing  
21 statistically significant increases in annual extreme flows being approximately balanced by the  
22 number showing a decrease. However there was some evidence for regionalization in behaviour;  
23 when data were pooled across all the rivers surveyed in Europe, a rising trend was found in the  
24 decade of the maximum observed daily flow with four times as many rivers showing the decade of  
25 highest flow in the 1990s than the 1960s.

26  
27 Milly et al (Milly *et al.* 2002) undertook a pooled study of great floods with return periods  
28 estimated as >100 yrs on very large rivers (with catchments greater than 200,000km<sup>2</sup>) in Asia,  
29 North America, South America, Europe and Africa. From the pooled record of all the rivers, the  
30 observed trend in the population of 100 year flood events, at a 95% confidence interval averaged  
31 across all basins, has been positive since the Mississippi Floods in 1993 and can be detected  
32 intermittently since 1972. Analysis of available long-term river flow records shows that since 1989  
33 more than half of Scotland's largest rivers (notably those draining from the west) have recorded  
34 their highest flows (Werrity *et al.* 2002). Of 16 rivers surveyed, with a median record of 39 years, 8  
35 had their maximum flow during 1989-1997 - a period of high North Atlantic Oscillation index  
36 values consistent with storm tracks bringing high levels of precipitation to northern Britain.

#### 37 38 1.3.8.2 *Extratropical cyclones*

39  
40 Many studies report an increase in the 1980s in the numbers of deep (and high wind speed)  
41 extratropical cyclone storms in the Atlantic margin of Northwest Europe (see Günther *et al.* 1998)  
42 returning to levels not previously seen since the late 19<sup>th</sup> Century. Various measures, including the  
43 number of deep storms (with central pressures less than 970hPa) and the annual pressure minimum  
44 of storms crossing the Greenwich Meridian all show a significant increase, in particular between  
45 1980 and 1993, when there were a series of major damaging storms. In the Northeast Atlantic wave  
46 heights showed significant increases over the period from 1970-1995 (Woolf *et al.* 2002) in parallel  
47 with the North Atlantic Oscillation NAO index (based on the pressure difference between Iceland  
48 and the Azores), which reached its highest values ever (reflecting deep low pressure over Iceland)  
49 in the years of 1989-1990. Intense storms returned at the end of the 1990s when there were three  
50 principal damaging storms across Western Europe in December 1999. However since that time, as  
51 winter NAO values have continued to fall (through to March 2005), there has been a significant

1 decline in the number of deep and intense storms passing into Europe to some of the lowest levels  
2 seen for more than 30 years.

3

#### 4 1.3.8.3 *Tropical cyclones*

5

6 While overall numbers of tropical cyclones worldwide have shown little variation over the past  
7 forty years (Pielke *et al.* 2005), the basin with the highest volatility in tropical cyclone numbers is  
8 the Atlantic, for which the record is considered comprehensive back to 1945. The number of years  
9 of high activity (8 or more) hurricanes in the Atlantic basin was four (out of 6 years) between 1950  
10 and 1955, only four in total in the low activity phase between 1956 and 1994 but eight out of eleven  
11 years between 1995 and 2005 (HURDAT 2005). The most intense Saffir Simpson Category 3-5  
12 storms have shown more variability than the overall population.

13

14 These shifts in hurricane activity and intensity are principally the consequence of sea surface  
15 temperature variations in the main hurricane development region of the tropical North Atlantic  
16 (Trenberth 2003; Emanuel 2005). From a low period of activity in the 1970s Emanuel identified an  
17 increase in the overall power dissipated by tropical cyclones hurricanes (measured from the  
18 Potential Destructiveness Index - that is the integral of the cube of the maximum wind speeds  
19 sampled over time along the track of the storm). Using this measure Emanuel identified an apparent  
20 doubling of the power released by tropical cyclones in both the Atlantic and North West Pacific  
21 basins over the past 30 years that in both basins appears to be correlated with the observed sea  
22 surface temperatures. This increase is significantly greater than had previously been anticipated on  
23 thermodynamic grounds based on the measured increases in sea-surface temperatures alone.  
24 Webster (Munich Re Group 2005) surveyed tropical cyclone intensities across all basins using  
25 satellite observations (that start in the 1970s) and found evidence for a shift in the proportion of  
26 intense tropical cyclones that reached the higher intensity (Saffir Simpson Cat4 and Cat 5) from  
27 close to 20% of the total in the 1970s rising to 35% since the 1990s.

28

29 However questions remain as to whether the record of tropical cyclone intensities may have been  
30 underestimated in the earlier period (see WMO/CAT Tropical Meteorology Research Program, 2006).  
31 The most reliable observations are likely to have come from the Atlantic Ocean where the link  
32 between observed sea surface temperatures and tropical cyclone intensities is widely accepted. For the  
33 Atlantic, there is also significant debate about the influence of an Atlantic Multidecadal Oscillation of  
34 tropical sea surface temperature variations relative to any rising trend accompanying global warming.

35

#### 36 1.3.8.4 *Economic and insurance losses*

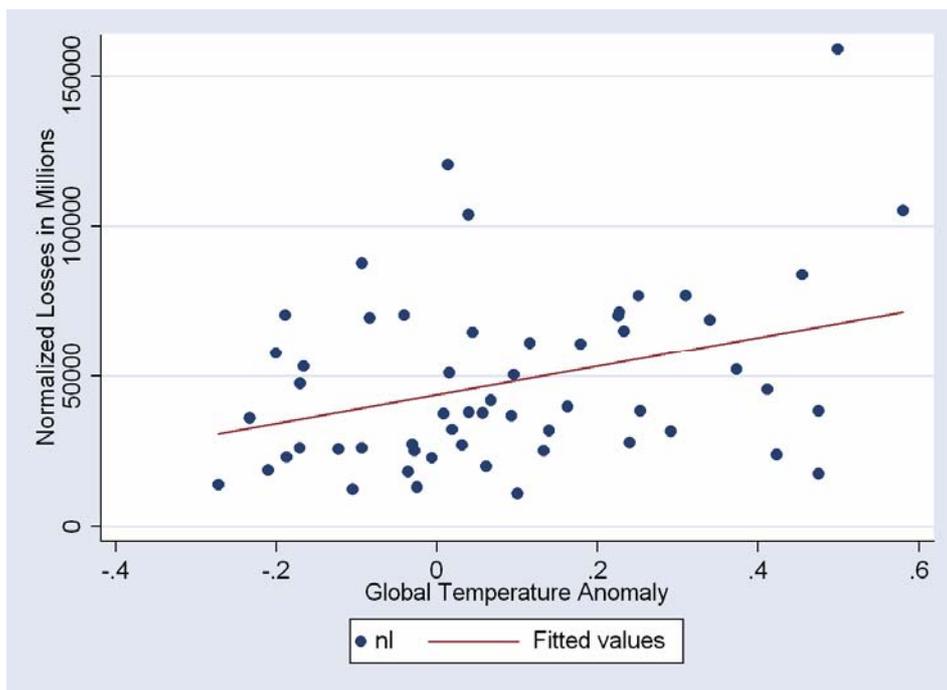
37

38 Economic losses attributed to natural disasters have increased from US \$75.5 billion in the 1960s to  
39 \$659.9 billion in the 1990s (a compound annual growth rate of 8%) (UNDP, 2004). Private sector  
40 data on insurance costs also shows rising insured losses over a similar period (Munich Re Group  
41 2005; Swiss Reinsurance Company 2005). However, as has been widely acknowledged, failing to  
42 adjust for time-variant economic factors yields loss amounts that are not directly comparable and a  
43 pronounced upward trend through time for purely economic reasons. A previous normalization of  
44 losses, undertaken for the United States hurricane by Pielke and Landsea (1998) and US flood  
45 (Pielke *et al.* 2002) included normalizing the economic losses for changes in wealth and population  
46 to express losses in constant dollars. These previous national US assessments, as well as those for  
47 normalized Cuban hurricane losses (Pielke *et al.* 2003), did not show an significant upward trend in  
48 losses over time, but this was before the remarkable hurricane losses of 2004 and 2005.

49

50 Miller (Miller *et al.* 2006) performed an analysis to construct a ‘global’ catalogue of catastrophe  
51 losses normalized to account for changes that have resulted from variations in wealth and the

1 numbers and values of properties located in the path of the catastrophes using the method of Pielke  
 2 and Landsea (1999). The global survey covered data from 1950 – 2005 for countries and regions  
 3 that had a reasonable centralization of catastrophe loss information as well as a broad range of peril  
 4 types: tropical cyclone, extratropical cyclone, thunderstorm, hailstorm, wildfire and flood, and that  
 5 spanned high and low latitude areas. These included the principal developed countries and regions  
 6 Australia, Canada, Europe, Japan, South Korea, US and developing: Caribbean, Central America,  
 7 China, India and the Philippines. For many countries in the survey data were incomplete before  
 8 1970 and for some, such as China it appears the record only becomes complete from the 1980s.  
 9  
 10 Once the data were normalized a small trend was found for an increase in annual catastrophe loss  
 11 since 1970 of 2% per year. However a significant trend was not found for the overall data on losses  
 12 since 1950 and normalized losses in the 1950s were higher than in the 1960s and 1970s (in part  
 13 because there were subsequent major investments in coastal flood protection schemes in Europe  
 14 and Japan). For a number of regions, such as Australia and India, normalized losses show a  
 15 statistically significant reduction since 1970. Since 1970 the global normalized results do show a  
 16 statistically significant correlation with global temperatures with an increase of \$6.6Bn (in 2005  
 17 values) for each 0.1C rise in global temperatures (Figure 1.5). However these findings of trends are  
 18 sensitive to modest changes in the assumptions. Removing the 2004 and 2005 years of US and  
 19 Caribbean hurricane losses, or major flood losses in China in the 1990s, or swapping US and India  
 20 ‘GDP per capita’ values means that the relationship between year and loss weakens or disappears  
 21 entirely.



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 42 **Figure 1.5:** Normalized losses in US\$ millions compared with global temperature anomalies  
 43 (Miller et al. 2006).

44  
 45 **1.3.8.5 Summary**

46  
 47 Global losses reveal rapidly rising costs due to extreme weather-related events since the 1970s.  
 48 While the dominant signal remains that of the significant increases in the values of exposure at risk,  
 49 once losses are normalised for exposure, there still remains an underlying rising trend. For specific  
 50 regions and perils, including extreme floods on some of the largest rivers, there is evidence for an  
 51 increase in occurrence. For tropical cyclones, in particular in the Atlantic Ocean and Northwest

1 Pacific, over the past 30 years, significant increases have occurred in the proportion of storms at the  
2 highest intensity (Categories 4 and 5) as well as in the cumulative ‘power dissipation’ of storms (a  
3 combination of intensity and duration) that correlates with increases in sea surface temperatures in  
4 the main cyclone development regions.

### 7 *1.3.9 Socio-Economic Indicators*

8  
9 Literature on observed changes in socio-economic indicators in response to recent climate change is  
10 sparse. Here we summarize some of the few examples related to energy demand and tourism now  
11 extant, and some studies on regional adaptations to climate trends. Relevant indicators include  
12 energy supply and markets for natural resources (e.g., timber, fisheries). Indicators of adaptation  
13 such as domestic insurance claims, energy demand, changes in tourism are being defined and  
14 tracked for the UK and Europe (DEFRA, 2003; EEA, 2004).

#### 16 *1.3.9.1 Energy Demand*

17  
18 Buildings account for a significant part of total energy use, up to 50% in some developed countries  
19 (Lorch 1990) (see WGIII Chapter 6), and the design and energy performance of buildings are  
20 related to climate (Steemers 2003). Work related to climate change and building energy use can be  
21 grouped into two major areas – weather data analysis and building energy consumption.

22  
23 *Weather data analysis.* A study on the 1981-1995 weather data by Pretlove (Pretlove and  
24 Oreszczyn 1998) indicated that temperature and solar radiation in the London region (UK) had  
25 changed significantly over the period, and climatic data used for energy design calculations could  
26 lead to 17% inaccuracies in building energy-use estimates. Based on 1976-1995 temperature data  
27 from 3 key UK sites, Levermore (Levermore and Keeble 1998) found that the annual mean dry-bulb  
28 temperature had increased by about 1°C over the 19-year period with milder winters and warmer  
29 summers. In subtropical Hong Kong, Lam (Lam *et al.* 2004) analyzed the 40-year period (1961-  
30 2000) weather data and found an underlying trend of temperature rise, especially during the last 10  
31 years (1991-2000). The increases occurred largely during the winter months and the impact on peak  
32 summer design conditions and cooling requirements, and hence energy use, was considered  
33 insignificant. In the 1990s and 2000s, many countries experienced extreme phenomena (notably,  
34 heat waves in summer), which induced exceptional peaks of electric power consumption (Klein  
35 Tank and Konnen 2003). These had notable impacts on human mortality (1.3.7) and the local socio-  
36 economic systems (Easterling *et al.* 2000; Parmesan *et al.* 2000; Johnson *et al.* 2004). Two well-  
37 documented cases are the heat waves in Chicago in 1995 (Karl and Knight 1997) and in Europe in  
38 2003 (Schar *et al.* 2004).

39  
40 *Building energy consumption.* Energy use has been and will continue to be affected by climate  
41 change because space conditioning, a major energy end-user, is climate-dependent. However, the  
42 extent to which temperature rise has affected energy use for space heating/cooling in buildings is  
43 uncertain. There is a concern that energy consumption will increase as air-conditioning is adopted  
44 for warmer summers (see Chapter 6). It is likely that certain adaptation strategies (e.g. tighter  
45 building energy standard) have been (or would be) taken in response to climate change (e.g.  
46 Camilleri *et al.* 2001; Larsson 2003; Sanders and Phillipson 2003; Shimoda 2003). Adaptation  
47 strategies and implementation are strongly motivated by the cost of energy. Besides, in terms of  
48 thermal comfort, there is also the question of people adapting to warmer climates (e.g. de Dear and  
49 Brager 1998; Nicol 2004).

#### 51 *1.3.9.2 Tourism*

1  
2 Climate is a major factor for tourists when choosing a destination (Aguiló *et al.* 2005) and both  
3 tourists and tourism stakeholders are sensitive to fluctuations in the weather and climate (Wall  
4 1998). Statistical analyses by Maddison (Maddison 2001), Lise and Tol (Lise and Tol 2002), and  
5 Hamilton (Hamilton 2003), and a simulation study by Hamilton (Hamilton *et al.* 2003) have shown  
6 the relevance of climatic factors as determinants of tourist demand, next to economic and political  
7 conditions, fashion, media attention, and environmental quality. As a result of the complex nature  
8 of the interactions that exist between tourism, the climate system, the environment, and society, it is  
9 difficult to isolate the direct observed impacts of climate change upon tourism activity. There is also  
10 sparse literature upon this relationship at all scales. Responses have been documented in  
11 Switzerland, Austria, the eastern U.S. and Chile (Breiling 1998; Elsasser and Messerli 2001;  
12 Steininger *et al.* 2002; Beniston 2003; Casassa *et al.* 2003; Hamilton 2003; Beniston 2004).

### 13 14 *1.3.9.3 Regional Adaptation*

15  
16 There are several studies that show societies adapting to climate changes such as drying trends or  
17 increasing temperatures. For example, in Southern Africa Thomas (Thomas *et al.* 2005; Thomas  
18 and Twyman 2005) examined responses to recent historical climate variability and change in four  
19 locations in southern Africa. They found that people were highly aware of changes in the climate  
20 including longer dry seasons and more uncertain rainfall, and were adjusting to change through  
21 collective and individual actions that included both short-term coping through switching crops and long  
22 term adaptations such as planting trees, and commercializing and diversifying livelihoods. One of the  
23 most striking conclusions was the importance of local institutions and social capital such as farming  
24 associations in initiating and supporting adaptations.

25  
26 In Europe, evidence is also accumulating that people are adapting to climate change, either in  
27 response to observed changes or in anticipation of predicted change. For example, in the UK a  
28 large number of adaptations have been identified including changes in flood management  
29 guidelines (assuming more extremes), hiring of climate change managers, alteration of nature  
30 conservation and disaster plans, climate proofing buildings, planting different crops and trees, and  
31 converting a ski to a walking centre in Scotland (West and Gawith 2005).

32  
33

## 34 **1.4 Larger-scale aggregation and attribution**

35  
36 Larger-scale aggregation may offer insights into the attribution of some of the observed changes  
37 described in 1.3 by combining the results from multiple studies over larger regions. As described in  
38 1.2, observed changes in systems and sectors are jointly attributed to anthropogenic climate change  
39 through a process involving attribution of the responses to regional temperature changes and  
40 attribution of the regional temperature changes to increases in greenhouse gases and aerosols in the  
41 atmosphere.

42  
43

### 44 *1.4.1 Larger-scale aggregation*

45  
46 This section evaluates studies that use techniques that aggregate from individual observations at  
47 sites to regional, continental, and global scales.

48  
49

#### 49 *1.4.1.1 Studies related to warming*

50  
51 Meta-analysis is a statistical method of combining quantitative findings from multiple studies

1 investigating similar factors for the purpose of finding a general result. The methods used in the  
2 various studies, however, need not be similar. The criteria for inclusion of studies in a meta-analysis  
3 are determined *a priori* and rigorously followed to avoid investigator effect.

4  
5 Parmesan and Yohe (Parmesan and Yohe 2003) and Root *et al.* (Root and Schneider 2002; Root *et al.*  
6 *et al.* 2003) have examined the ‘fingerprint’ of observed warming in recent decades on the phenology  
7 and distribution of plants and animal species using meta-analyses. Although the detailed results of  
8 these studies are different, because they used different species and different methods, they all  
9 conclude that a significant impact of global warming is already discernible in animal and plant  
10 populations at regional and continental scales in the Northern Hemisphere.

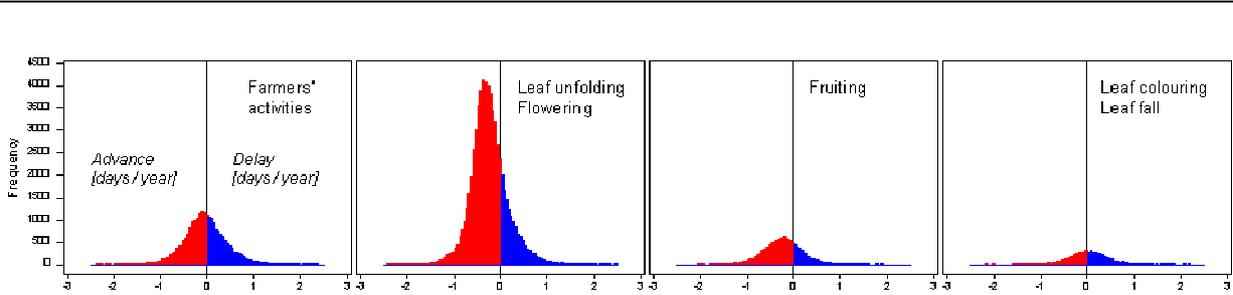
11  
12 Parmesan (Parmesan and Yohe 2003) applied meta-analysis techniques to 31 studies that examined  
13 more than 270 species, and showed that recent biological trends matched climate change  
14 predictions. Their meta-analyses estimated northward range shifts of 6.1 km/decade for northern  
15 range boundaries of species living in the northern hemisphere and documented advancement of  
16 spring events in northern hemisphere species by 2.3 d/decade in the northern hemisphere. They also  
17 defined a diagnostic fingerprint of temporal and spatial ‘sign-switching’ responses uniquely  
18 predicted by twentieth century climate trends. Among long-term/large-scale/multi-species data sets,  
19 this diagnostic fingerprint was found for 279 species. They concluded, with ‘very high confidence,’  
20 that climate change is already affecting living systems.

21  
22 After examining over 2,500 articles on climate change and a wide array of species from around the  
23 globe, Root and co-authors (Root *et al.* 2005) found that 143 studies fit the criteria for inclusion in  
24 their meta-analyses. They focused on only those species showing a change and found that about  
25 80% of the species showing change were changing in the direction expected with warming. The  
26 types of changes included species expanding their ranges poleward and higher in elevation, and  
27 advances in the timing of spring events, such as flowers blooming and frogs chorusing, by about 5  
28 days per decade in the last 30 years. This number is larger than the 2.3 d/decade found by Parmesan  
29 and Yohe (Parmesan and Yohe 2003) because these authors included both changing and not-  
30 changing species in their analysis, while Root and co-authors only included changing species. A  
31 more recent meta-analysis of bird arrival dates (Lehikoinen *et al.* 2004) showed strong evidence of  
32 earlier arrival. Of 983 data series, 39% were significantly earlier and only 2% significantly later for  
33 first arrival dates.

34  
35 The EU COST725 network analysis project had as its main objective the establishment of a  
36 European reference data set of phenological observations that can be used for climatological  
37 purposes, particularly climate monitoring and detection of changes (see Box 1.3).

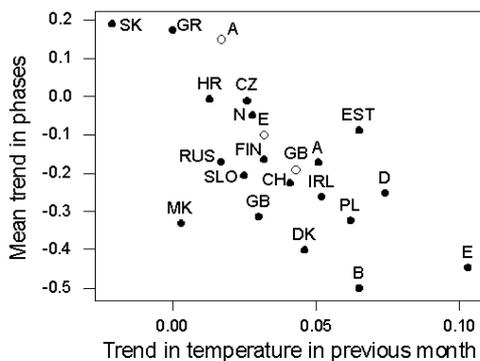
### 40 ***Box 1.3: Phenological Responses to Climate in Europe: The COST725 Project***

41  
42 The COST725 meta-analysis-project used an enormous phenological network dataset of more than 125,000  
43 observational series of various phases in 542 plant and 19 animal species in 21 European countries (1971-  
44 2000). The time-series were systematically (re-)analysed for trends in order to track and quantify the  
45 phenological response to changing climate. The benefit of this study is a verification and exhaustive  
46 enlargement of nationally reported trends at single-sites and / or for selected species, which are particularly  
47 open to suspicion of being biased towards predominantly reporting climate change induced impacts. Species’  
48 phenology (254 national series) was responsive to temperature of the preceding month with spring / summer  
49 phases advancing on average by 2.5 days/°C, leaf colouring /fall being delayed by 1.0 day/°C.



The summary of more than 100 000 trends revealed a clear signal across Europe of changing spring phenology with 78 % of leaf unfolding and flowering records advancing (31% significantly) and only 22% delayed (3% significantly). Fruit ripening was mostly advanced (75% advancing, 25% sig.; 25% delayed, 3% sig.). The signal in farmers' activities was generally smaller (57% advancing, 13% sig.; 43% delayed, 6% sig.). Autumn trends (leaf colouring/fall) were ambiguous. Spring and summer exhibited a clear advance by 2.5 days/decade in Europe, mean autumn trends were close to zero, but suggested more of a delay when the average trend per country was examined (1.3 days/decade).

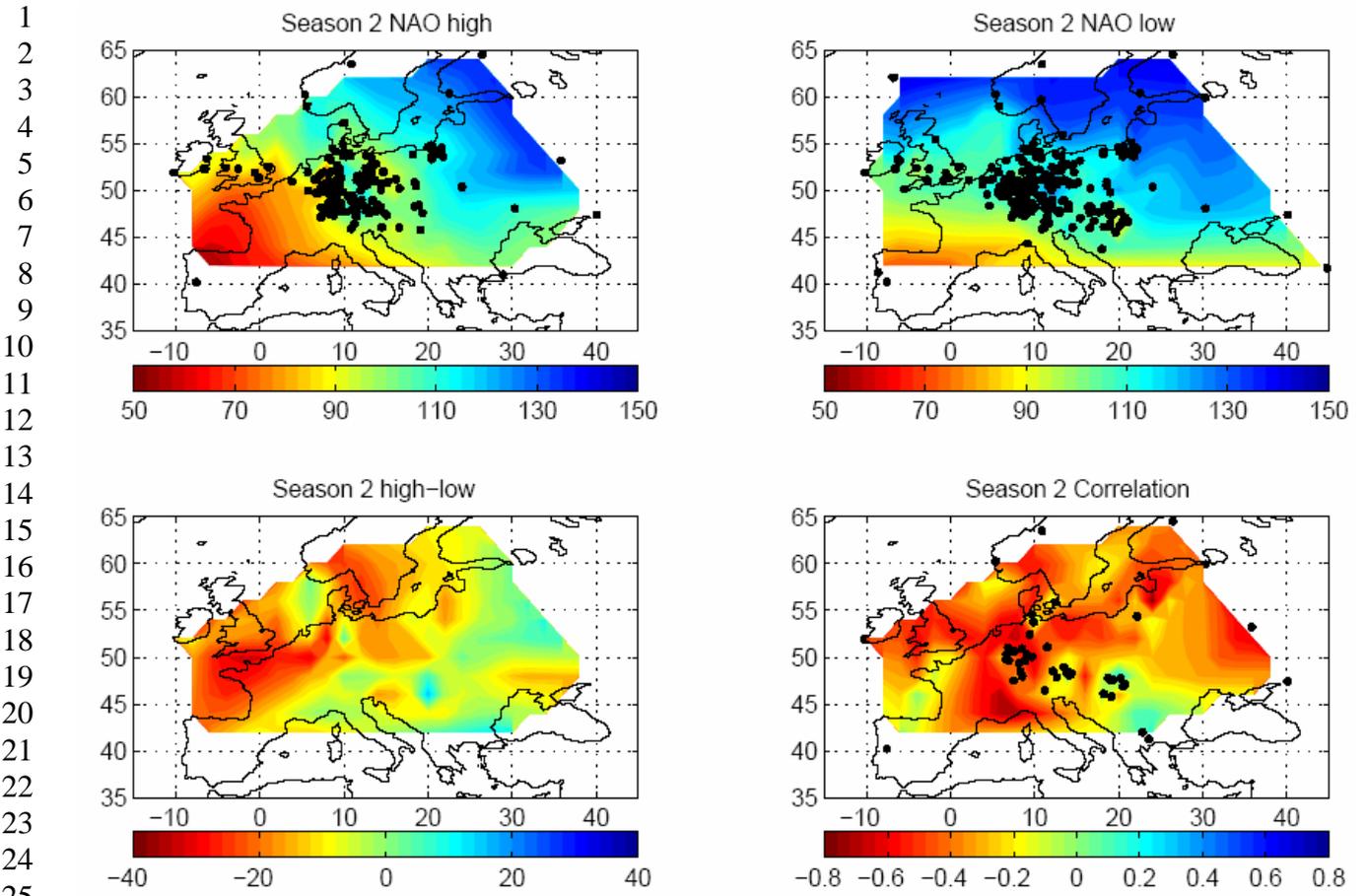
Leafing, flowering phases and spring animal phases



The pattern of observed change in spring (leafing, flowering, animal phases) was spatially consistent and efficiently matched measured national warming across 19 European countries (correlation coefficient  $r = -0.69$ ,  $p < 0.001$ ), thus the phenological evidence quantitatively mirrored regional climate warming. The COST725 results assessed the possible lack of evidence at a continental scale as 20% (c.80% of spring / summer phases advancing). They strongly support previous results and confirm them as being free from bias towards reporting global change impact (Menzel *et al.* 2006).

1.4.1.2 Studies related to multi-decadal climate variability

The North Atlantic Oscillation (NAO) has widespread influence on many ecological processes. A comprehensive, long-term European plant phenological dataset (1879-1998), including in total 23,797 stations of (1) the historical first European Phenological Network (1882-1941), (2) the network of the International Phenological Gardens in Europe (1959-1998), and (3) network data of seven Central and Eastern European countries (1951-1998, EU FP5 project POSITIVE), was analysed to study the influence of NAO of the progression (direction, velocity) of nine phenological seasons across Europe (Menzel *et al.* 2005). Phenological phases in most of the area studied responded to higher NAO indices by earlier spring leaf unfolding and flowering, the correlation coefficients between mean onset and NAO ranged up to 0.8 (Fig 1.6, lower plate right). This did not necessarily implicate a high relevance of the NAO index in all regions in Europe. Differences in onset between the average NAO high and average NAO low years were more pronounced in the western (France, Ireland, UK) and north-western (south Scandinavia) parts of Europe and less distinct in the continental part of Europe (lower left panel). The two different patterns of progression are clearly evident SW-NE in years with high NAO index and S-N in years with low NAO index.



**Figure 1.6.** Upper two plates: The mean onset of season 2 (mid spring, day of the year) in Europe for the 10 years with the highest (1990, 1882, 1928, 1903, 1993, 1910, 1880, 1997, 1989, 1992, North Atlantic Oscillation (NAO) high) and the ten years with the lowest (1969, 1936, 1900, 1996, 1960, 1932, 1886, 1924, 1941, 1895, NAO low) NAO winter and spring index (Nov – Mar) in 1879-1998; Lower plate left: differences between the mean onset of season 2 (days) in NAO high and low years (upper two plates); Lower plate right: correlation coefficient between the yearly onset of season 2 and NAO index (1879-1998). The vertical and horizontal axes represent degrees of latitude and longitude respectively (Menzel et al. 2005).

Various other studies have found connections between local ecological observations and weather/climate patterns at larger spatial scales, particularly with large-scale climate variations associated with the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO), and Pacific Decadal Oscillation. Impacts have been demonstrated across diverse taxa (birds, mammals, fish). NAO has been associated with the synchronization of population dynamics of caribou and musk oxen (Post and Forchhammer 2002). Weladji and Holand (Weladji and Holand 2003) identified risks to northern indigenous peoples due to the negative impacts of higher NAO indices upon reindeer calf survival. Three recent studies identified the impacts of NAO on fish, including abundance (Guisande et al. 2004), phenology (Sims et al. 2004), and range shifts (Dulcic et al. 2004). A meta-analysis of ecological studies of NAO interactions found a clear NAO signature in freshwater, marine, and terrestrial ecosystems (Blenckner and Hillebrand 2002).

Bird populations and migratory timing have received particular attention. Huppopp and Huppopp (Huppopp and Huppopp 2003) find significantly earlier arrival of 17 species of migratory birds in Helgoland, Germany. For 23 of the 24 species studied, earlier arrival coincided with warmer local temperatures and correlation with higher NAO indices. Similarly, in the Czech Republic, Hubalek

1 (Hubalek 2003) found that the earlier arrival of short-distance migrants correlated with positive  
2 winter/spring NAO index values. Pied flycatchers across Europe are breeding earlier and laying  
3 smaller clutches; these changes are correlated with increased spring temperatures and positive  
4 values of the winter NAO index (Sanz 2003). With the exception of Ballard and co-authors'  
5 (Ballard *et al.* 2003) study of population declines of songbirds in western North America, other  
6 recent avian studies have strongly linked NAO and/or ENSO to demographic dynamics, but do not  
7 attribute climate patterns to population trends (Sydeman *et al.* 2001; Jones *et al.* 2002; Almaraz and  
8 Amat 2004).

#### 11 **1.4.2 Joint attribution**

13 Joint attribution involves attribution of significant changes in a natural or managed system to  
14 regional temperature changes, and attribution of a significant fraction of the regional temperature  
15 change to human activities. To date, two studies have demonstrated joint attribution directly using  
16 climate model studies; one using forest fires in Canada (Gillett *et al.* 2004), and the other using wild  
17 plants and animals (Root *et al.* 2005). An assessment of the relationship between significant  
18 observed changes in systems and sectors from 1.3 and attributable regional temperature change is  
19 presented in 1.4.2.3.

##### 21 *1.4.2.1 Attributing regional temperature change*

23 Since the TAR, it has been shown that an anthropogenic climate change signal is detectable in  
24 continental-scale regions using surface temperature changes over the 20<sup>th</sup> century (Karoly *et al.*  
25 2003; Stott 2003; Zwiers and Zhang 2003; Karoly and Braganza 2005) (See Chapter 9, Volume 1,  
26 for a more complete assessment of attribution of observed regional climate changes to  
27 anthropogenic forcing). Most of the observed warming over the last 50 years in the six major  
28 continents, including North America, Eurasia and Australia, is likely to be due to the increase in  
29 greenhouse gases in the atmosphere (Stott 2003). Many features of the observed temperature  
30 variability and change on decadal time scales in different regions are reproduced by the climate  
31 model simulations that include changes in anthropogenic forcing (see Fig. 9.4.7 in Volume 1).  
32 Recently, studies have shown that the observed regional warming trends over the last 50 and 30  
33 years are statistically significant in many regions of the globe, even for regions of order 500 km  
34 (Karoly and Wu 2005; Tett *et al.* 2005; Knutson and et al 2006). These warming trends are  
35 consistent with the response to increasing greenhouse gases and sulphate aerosols and cannot be  
36 explained by natural internal climate variations or the response to changes in natural external  
37 forcing (solar irradiance and volcanoes). Hence, the observed warming trends can be attributed to  
38 anthropogenic climate change in many regions of the globe.

40 The influence of anthropogenic forcing has also been detected in other climate changes over the last  
41 50 years, including increases in global oceanic heat content, increases in sea level, shrinking of  
42 alpine glaciers, reductions in Arctic sea ice extent, and reductions in spring snow cover (Hegerl *et al.*  
43 2007) (WGI AR4 Chapter 9).

##### 45 *1.4.2.2 Joint attribution using climate model studies*

47 One of the main messages of the SAR was that there is a discernible impact of humans on climate.  
48 A main message from the TAR was that wild plant and animal species were being affected by  
49 changes in regional temperatures. Now research has shown that these two findings can be combined  
50 to demonstrate that discernible changes in species at a regional scale are associated with regional  
51 temperatures, and that a significant amount of change in those temperatures, as determined by

1 climate modelling, is due to human activities (Root et al, 2005). This is what we are calling joint  
2 attribution.

3  
4 Root (Munich Re Group 2005) demonstrate joint attribution at a regional scale by considering  
5 changes in wild animals and plants. Using 145 species reported in 29 studies, they calculated the  
6 mean annual phenological change for species in the Northern Hemisphere (Figure 1.7a). These  
7 changes have been shown either in the original studies or in Root *et al.* (2001; 2003) to be  
8 statistically significantly associated with the changes in regional temperature changes.

9  
10 Modelled temperature data obtained from the HadCM3 GCM were used to determine if the changes  
11 in temperatures with which the phenological changes in species were associated were due to human  
12 or natural causes. Three different forcings were used when deriving the modelled values: natural  
13 only, anthropogenic only, and combined natural and anthropogenic. The association is quite poor  
14 between the phenological changes in species and modelled temperatures derived using only natural  
15 climatic forcing (Figure 1.7b). Quite strong agreement occurs, however, between the same  
16 phenological changes in species and temperatures modelled either using only anthropogenic forcing  
17 or using both natural and anthropogenic forcings together (Figure 1.7c & d). Studies comparing  
18 anthropogenically forced models to empirical data in the oceans (Barnett *et al.* 2004) and for  
19 planetary radiation balance (Hansen and Nazarenko 2004) reach similar conclusions using very  
20 different data sets and models: that there is discernible skill in models driven by anthropogenic  
21 forcing (see Chapter 9 of Working Group 1).

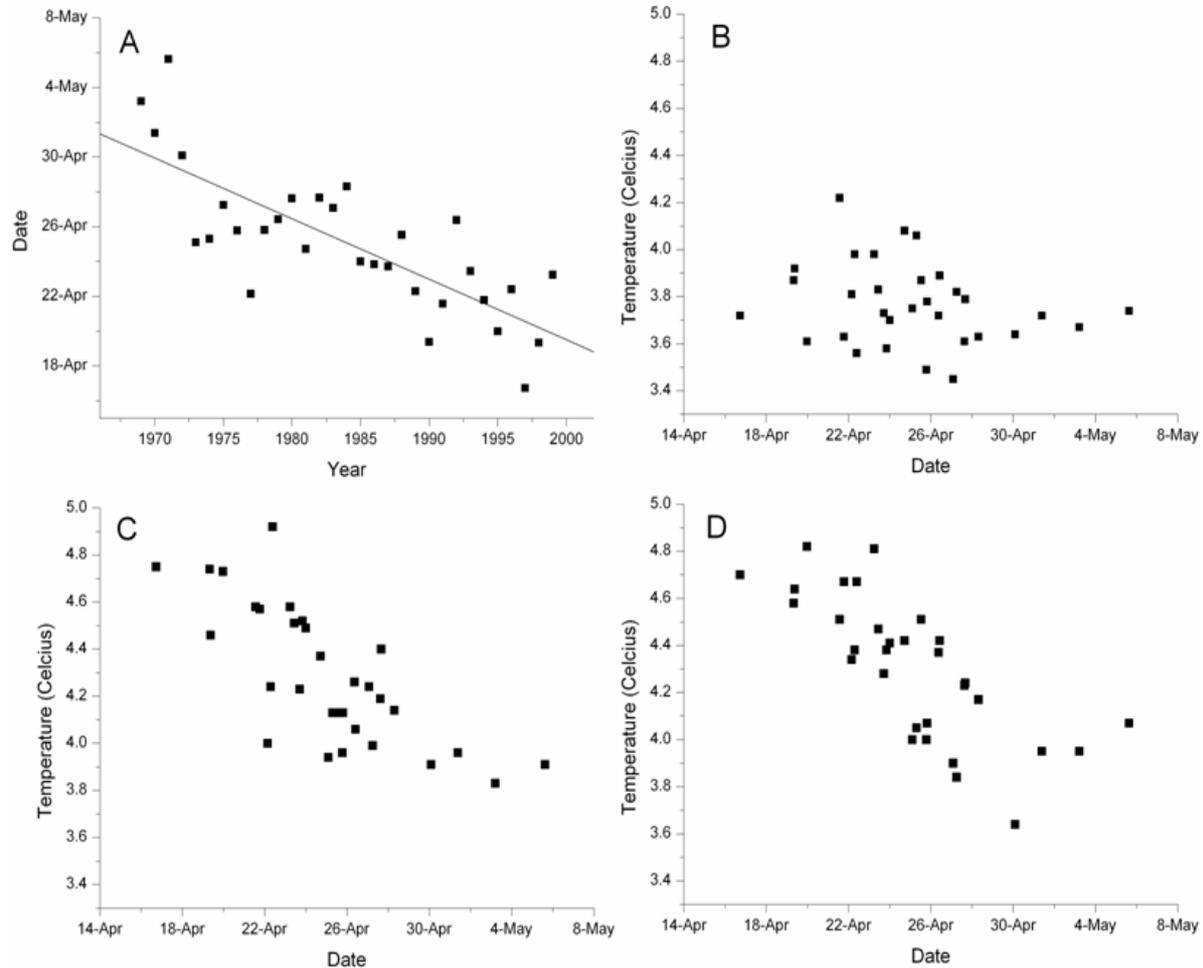
22  
23 In a related model-based joint attribution study, Gillett *et al.* (2004) demonstrated a striking  
24 agreement between the observed increase in the area of forests burned in Canada over the last four  
25 decades and that expected from climate changes due to increasing greenhouse gases and sulphate  
26 aerosols. Temperature is a good predictor of forested area burned (Flannigan and Harrington 1988).  
27 Using climate model simulations, Gillett and colleagues found that human activity has made a  
28 discernible contribution to the observed increase in temperature, which is outside the range of  
29 natural variability. They then used an empirical model of the relationship between climate  
30 variables and area burnt to show that the human-induced warming has had a detectable influence on  
31 the amount of forest area burnt.

#### 32 33 *1.4.2.3 Joint attribution from synthesis of studies*

34  
35 Significant observed changes documented since the TAR are divided into the categories of  
36 cryosphere, hydrology, coastal processes, marine and freshwater biological systems, terrestrial  
37 biological systems, and agriculture and forestry as assessed in 1.3. Studies are selected that  
38 demonstrate a statistically significant trend in change in system or sector related to temperature or  
39 other climate change variable for the period 1973-2002 (study periods may extend later), with at  
40 least 20 years of data. Studies are divided in three types: Type 1 studies are comprised of individual  
41 observations considered individually in the statistical analyses; Type 2 studies are comprised of  
42 individual observations that have been grouped and then “collectively analyzed” (i.e., statistically  
43 significant as a group, such as a network; Type 3 studies correspond to very large areas not  
44 associated with individual sites. Observation in the studies are characterized as ‘change in expected  
45 direction,’ ‘no change,’ and ‘change in unexpected direction.’

46  
47 Figure 1.8 shows the 5°x5° gridboxes in which significant warming trends over 1973-2002 are  
48 consistent with response to anthropogenic forcing and not consistent with internal climate variability  
49 alone for three GCMs (HadCM2) (Károly and Wu, 2005), and the geographic locations of significant  
50 observed changes from Type 1, 2, and 3 studies. A statistical comparison shows that the agreement  
51 between the regions of significant and attributable regional warming across the globe and the locations

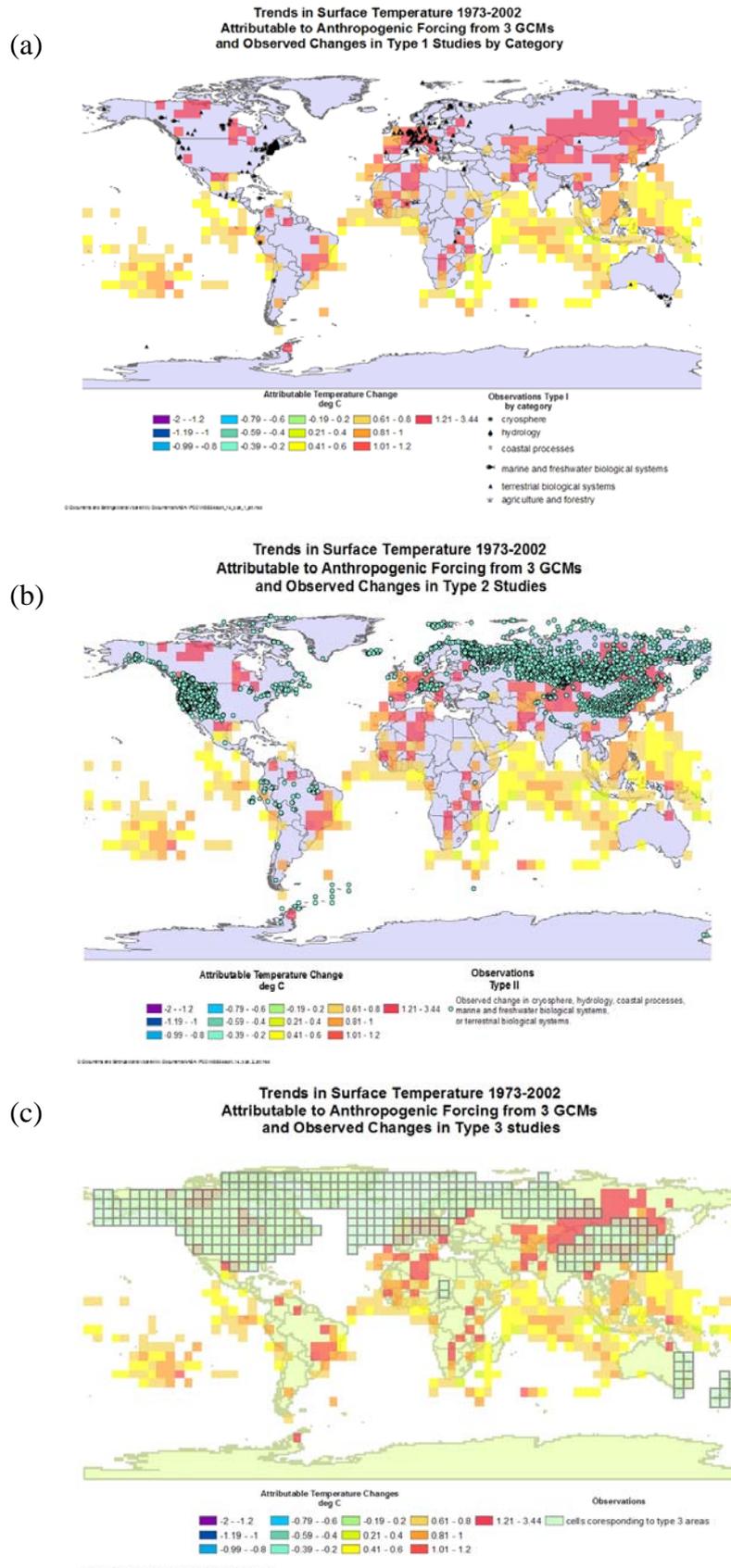
1 of significant observed changes in systems consistent with warming is very unlikely to be due to  
 2 natural variability in temperatures or natural variability in the systems (Supplementary Material).  
 3 Areas with joint attribution are found predominantly in the Northern Hemisphere high latitudes.



31 **Figure 1.7:** For each year, the dates (in Julian days) that spring events occurred in wild plants and  
 32 animals (e.g., timing of first bloom, arrival of spring migrants) are averaged over all Northern  
 33 Hemisphere species exhibiting statistically significant changes in those events ( $n=130$ ). These  
 34 averages are plotted against: A. year with a  $-3.2$  day change per decade ( $r^2=??$ ), B. the average  
 35 modelled spring (March, April, May) temperatures including only natural forcings at each study  
 36 location ( $r = 0.22, p<0.23$ ), C. the same as B except including only anthropogenic forcings ( $r = -$   
 37  $0.71, p<0.001$ ), and D. the same as B except including both natural and anthropogenic forcings ( $r$   
 38  $= -0.72, p< 0.001$ ). From Root et al. (2005).

41 The synthesis also enables examination of areas with significant change in temperature, but absence  
 42 of observations of changes in systems or sectors. Figure 1.9 shows observed surface-air temperature  
 43 changes from 1973-2002 with gridcells with significant temperature trends indicated. The climate  
 44 data used are from the  $5^{\circ} \times 5^{\circ}$  dataset from Hadley Centre and NOAA, and from GCOS (Global  
 45 Climate Observing System) station data (from stations designated as high quality). Using  
 46 information from Figure 1.9 and the observations from Type 1, 2 and 3 studies, Table 1.12 shows  
 47 the presence/absence and characterization of regional temperature changes and observed responses.

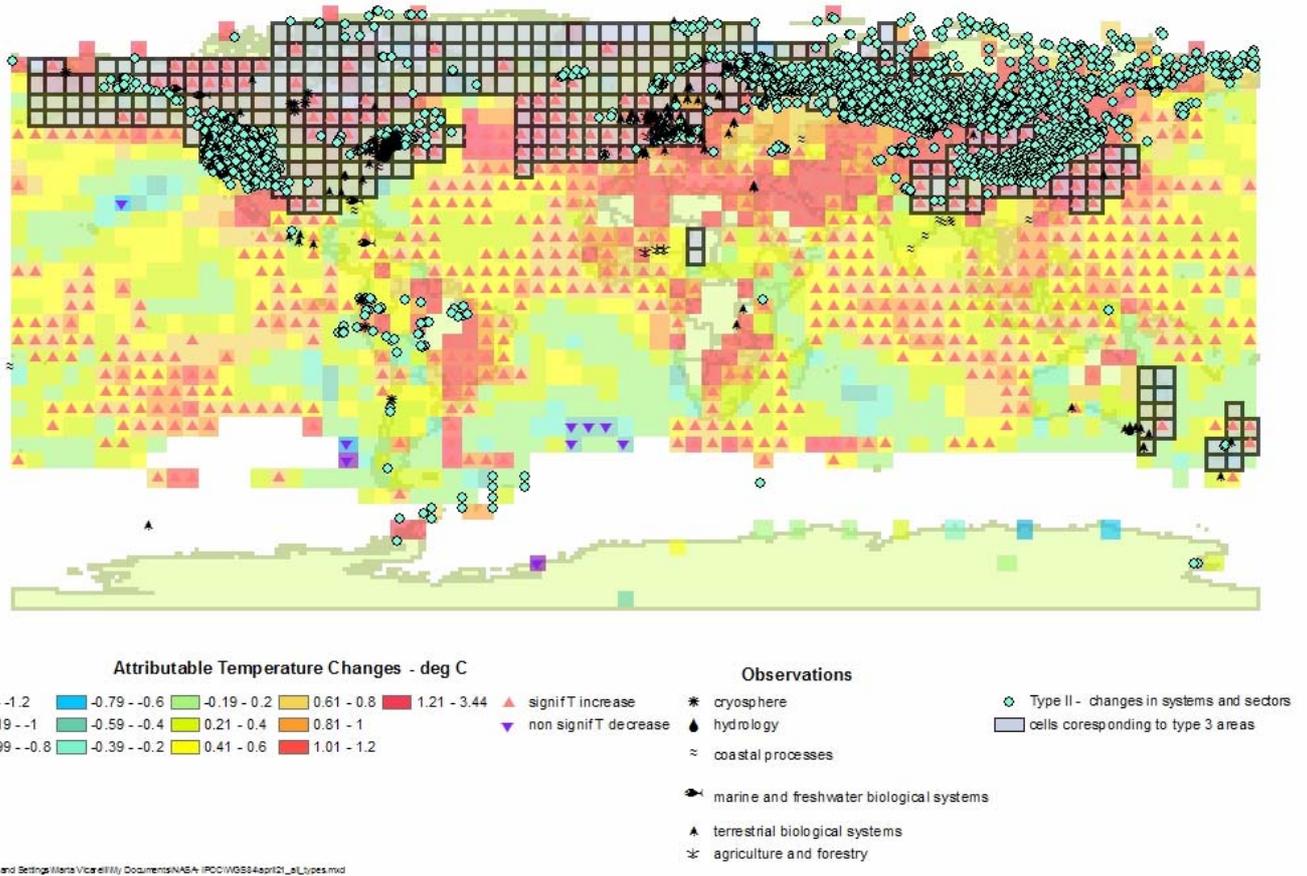
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**Figure 1.8:** Regional temperature warming attributable to anthropogenic forcing for three global climate models (HadCM2, GFDLR30, PCM) and a) Categories of Type 1 studies (individual observations considered individually in the statistical analyses; b) Observations of Type 2 studies (individual observations that have been grouped and then “collectively analyzed” (i.e., statistically significant as a group); and c) Areas of Type 3 studies (studies corresponding to very large areas not associated with individual sites). (Draft.)

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### Trends in Surface Temperature 1973-2002 and Observed Changes in Type 1, 2 and 3 studies



**Figure 1.9:** Observed trends in surface air temperature and sea-surface temperature 1973-2002 (Karoly and Wu, 2005). Individual 5° latitude-longitude regions are indicated where the observed trends are significantly larger than zero at the 95% level. White regions do not have sufficient observational climate data to estimate a trend. Observed changes in cryosphere, hydrology, coastal processes, marine and freshwater biological systems, terrestrial biological systems, and agriculture and forestry for studies ending in 1993 or later with at least 20 years of data. (Draft.)

There are many 5° gridboxes that are experiencing significant warming for which there are no observations of changes in systems or sectors. For regions where there are both significant warming and observed changes, there is a greater probability of finding coincident significant temperature change and observed responses in the expected direction than finding significant temperature change and no response or response in an unexpected direction. In regions with no change in temperature, there is a greater probability of finding no observed response than of finding an observed response in either direction.

1  
2 **Table 1.12:** Presence/absence of observed changes in systems and sectors and presence/absence  
3 of significant regional temperature change, with characterization of observed changes as  
4 ‘consistent with warming,’ or ‘not consistent with warming,’ for a) Type 1 studies (individual  
5 observations considered individually in statistical analysis), b) Type 2 studies (individual  
6 observations that have been grouped and ‘collectively’ analyzed), and c) Type 3 studies (studies  
7 corresponding to very large areas not associated with individual sites).  
8

9 a) Type 1 studies (individual observations analyzed individually).

Type 1	Cells with significant system/sector change consistent with warming	Cells without significant system/sector change	Cells with significant system/sector change not consistent with warming	Cells with no studies	Total
Cells with positive significant temperature change	30	6	1	721	758
Cells without significant temperature change	25	0	0	893	918
Cells with negative significant temperature change	0	0	0	9	9
Cells with no temperature data	5	1	0	829	835
Total	83	7	1	2452	2520

10  
11 b) Type 2 studies (individual observations that have been grouped and ‘collectively’ analyzed).

Type 2	Cells with significant system/sector change consistent with warming	Cells without significant system/sector change	Cells with significant system/sector change not consistent with warming	Cells with no studies	Total
Cells with positive significant temperature change	109	9	1	639	758
Cells without significant temperature change	141	11	7	759	918
Cells with negative significant temperature change	0	0	0	9	9
Cells with no temperature data	62	0	0	773	835
Total	312	20	8	2180	2520

12

1 c) Type 3 studies (studies corresponding to very large areas not associated with individual sites).

Type 3	Cells with significant system/sector change consistent with warming	Cells without significant system/sector change	Cells with significant system/sector change not consistent with warming	Cells with no studies	Total
Cells with positive significant temperature change	139	0	0	619	758
Cells without significant temperature change	185	0	0	733	918
Cells with negative significant temperature change	0	0	0	9	9
Cells with no temperature	67	0	0	768	835
Total	391	0	0	2129	2520

2  
3

4 Uncertainties in observed change studies at the regional level relate to potential mismatches  
5 between climate and system/sector data in temporal and spatial scales and lack of time-series of  
6 sufficient length to determine if the changes are outside normal ranges of variability. The issue of  
7 non-climate driving forces is also important. Land use change, changes in human management  
8 practices, pollution, and demography shifts are all, along with climate, drivers of environmental  
9 change. More explicit consideration of these factors in observed change studies will strengthen the  
10 robustness of conclusions.

11  
12 Since systems and sectors respond to an integrated climate signal, precise assignment of the  
13 proportions of natural and anthropogenic forcings in their responses is not possible. Through the  
14 use of combined observational and simulation studies, observed changes may be used to test the  
15 presence of the anthropogenic signal. The wide variety of observed responses to regional climate  
16 trends in expected directions, and the attribution of the regional climate trends to anthropogenic  
17 causes means that anthropogenic climate change is having a significant impact on multiple systems  
18 and sectors in many regions across the globe.

19  
20

#### 21 **1.4.3 Learning from current and observed responses – adaptation and vulnerability**

22  
23  
24

In relation to the questions posed in 1.1.2, we find the following:

25 1) *Detection*. Significant changes in systems and sectors related to changes in regional climate are  
26 detectable through a variety of methods of analysis. These methods include analyses of ground-  
27 based data from individual sites, networks of sites, large-area collections, as well as remote sensing.  
28 Meta-analyses across multiple studies are used to detect and characterize changes.

29

30 2) *Functional Understanding*. The great majority of observed changes are consistent with  
31 functional understanding and modelled predictions of climate impacts. Examples of expected  
32 responses include infrastructure effects of melting in the cryosphere, effects of intensifying

1 droughts and runoff, and effects of rising sea-levels. In marine, freshwater, and terrestrial biological  
2 systems, changes in morphology, physiology, phenology, reproduction, species distribution,  
3 community structure, ecosystem processes, and species evolutionary processes are, for the most  
4 part, in predicted directions. Agricultural crops have shown similar trends in phenology, and  
5 management practices along with the spread of pests and diseases coincide with expected responses  
6 to warming. Responses of yields in some crops coincide with model predictions. With human  
7 health, there is spread of temperature-sensitive vectors, e.g., ticks. With the warmer sea surface  
8 temperatures and the intensification of the hydrological cycle comes evidence of an expected  
9 increase in damages from floods and tropical cyclones.

10  
11 3) *Prevalence and Patterns*. Observed changes are prevalent across diverse physical and biological  
12 systems and less prevalent in managed sectors and across many, but not all geographical regions.  
13 While there is evidence of observed changes in every continent, including Antarctica, the majority  
14 of studies provide evidence of observed changes in Northern Hemisphere high latitudes and  
15 altitudes. Significant evidence comes from high-latitude waters in the Northern Hemisphere as well.  
16 Evidence is primarily found in places where warming is the greatest. Documentation of observed  
17 changes in tropical regions is still sparse.

18  
19 4) *Adaptation and Vulnerability*. The evidence extant for adaptation and vulnerability to observed  
20 climate change is most prevalent in places where warming has been the greatest and in systems that  
21 are more sensitive to temperature. Thus, there are documented changes related to adaptation in the  
22 Arctic and mountain regions that include reduced outdoor and tourism activities, and alterations in  
23 indigenous livelihoods (1.3.1). Responses to climate change, including warming, vary by  
24 community and are beginning to be systematically documented. In regard to sea level rise, there are  
25 only a few isolated cases of historic island abandonment have been documented, although residents  
26 of presently inhabited islands such as Tuvalu, are finding it increasingly difficult to maintain their  
27 lifestyles, due to climate-induced environmental changes (1.3.3).

28  
29 In managed systems, there is little documented evidence of adaptation to regional climate trends in  
30 agriculture and forestry, with only a few studies related to the shift of sowing dates of annual crops  
31 (1.3.6). There is even less evidence related to food supply. In regard to vulnerability, there are few  
32 studies of observed effects of warming in subsistence agricultural systems in rural populations in  
33 developing countries; there are documented studies of adaptive responses and vulnerability to long-  
34 term drought in the Sahel. Vulnerability appears to be high in the case of extreme events or  
35 exceptional episodes even in developed countries, as documented by the agricultural response and  
36 excess mortality to the 2003 heatwaves in Europe. In human health, adaptation to high temperature  
37 via air-conditioning has contributed to declines in death rates during the summer in the U.S. and  
38 Europe over the past 30-40 years (1.3.7). Documentation of adaptation and vulnerability in terms of  
39 energy and tourism is limited (1.3.9).

40  
41 5) *Attribution to Anthropogenic Forcing*. The wide variety of observed responses to regional  
42 climate trends in expected directions, and the attribution of the regional climate trends to  
43 anthropogenic causes means that anthropogenic climate change is having a significant impact on  
44 multiple systems and sectors in many regions across the globe. Regions with climate warming  
45 attributable to anthropogenic forcing with an accumulation of evidence of observed changes are  
46 Europe, Northwestern Asia, Central Asia, northwestern North America, and the North Atlantic.  
47 Regions with attributable warming where evidence of observed changes is sparse are Africa and  
48 South America, and is lacking in Southeast Asia, the Indian Ocean and regions in the Pacific.

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